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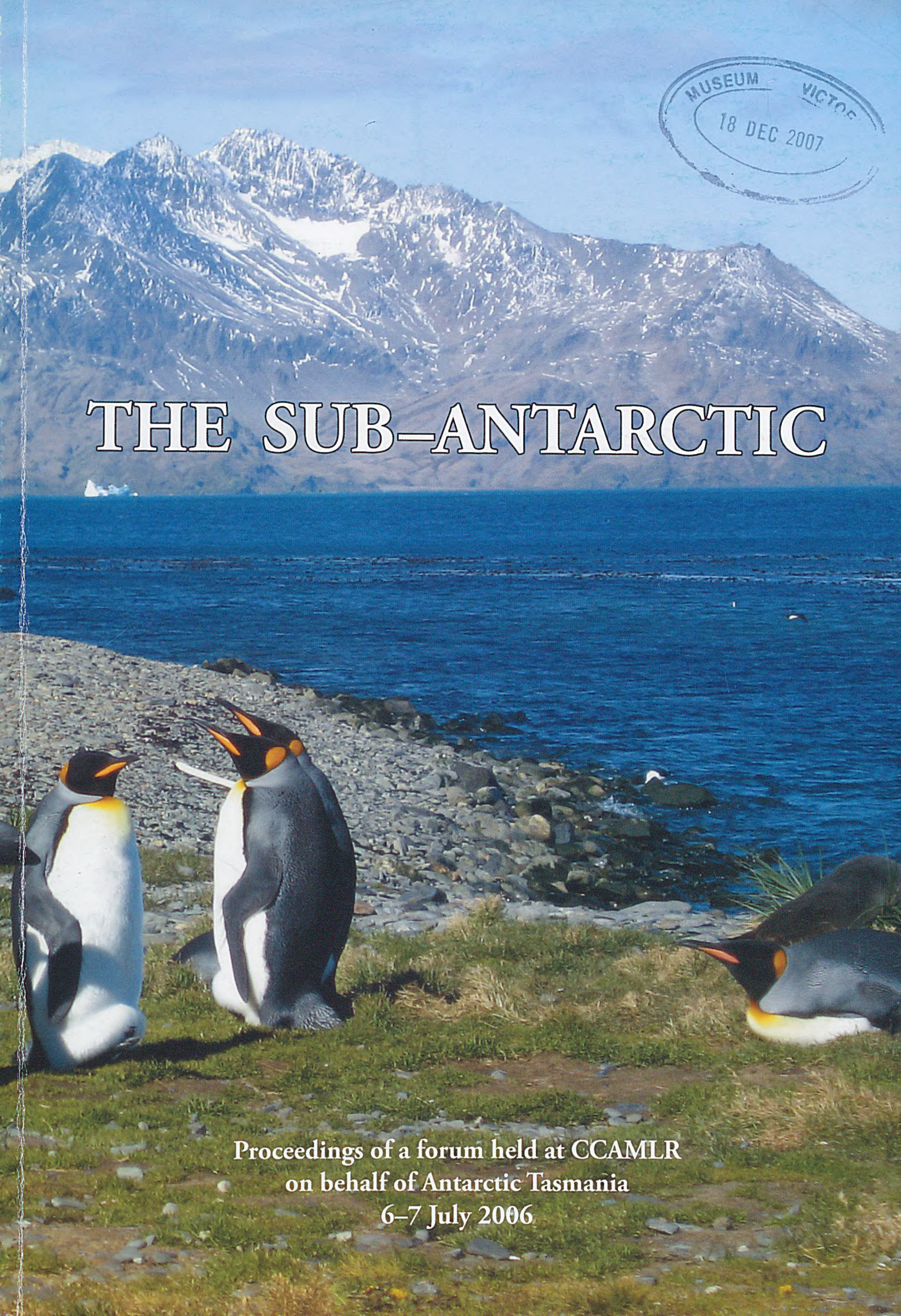

Proceedings of a forum held at CCAMLR
on behalf of Antarctic Tasmania
6–7 July 2006

PAPERS AND PROCEEDINGS OF

THE ROYAL SOCIETY OF TASMANIA

Edited by Patricia M. Selkirk,
Patrick G. Quilty and
Margaret Davies

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6–7 July 2006

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PAPERS AND PROCEEDINGS OF THE ROYAL SOCIETY OF TASMANIA
VOLUME 141, PART 1

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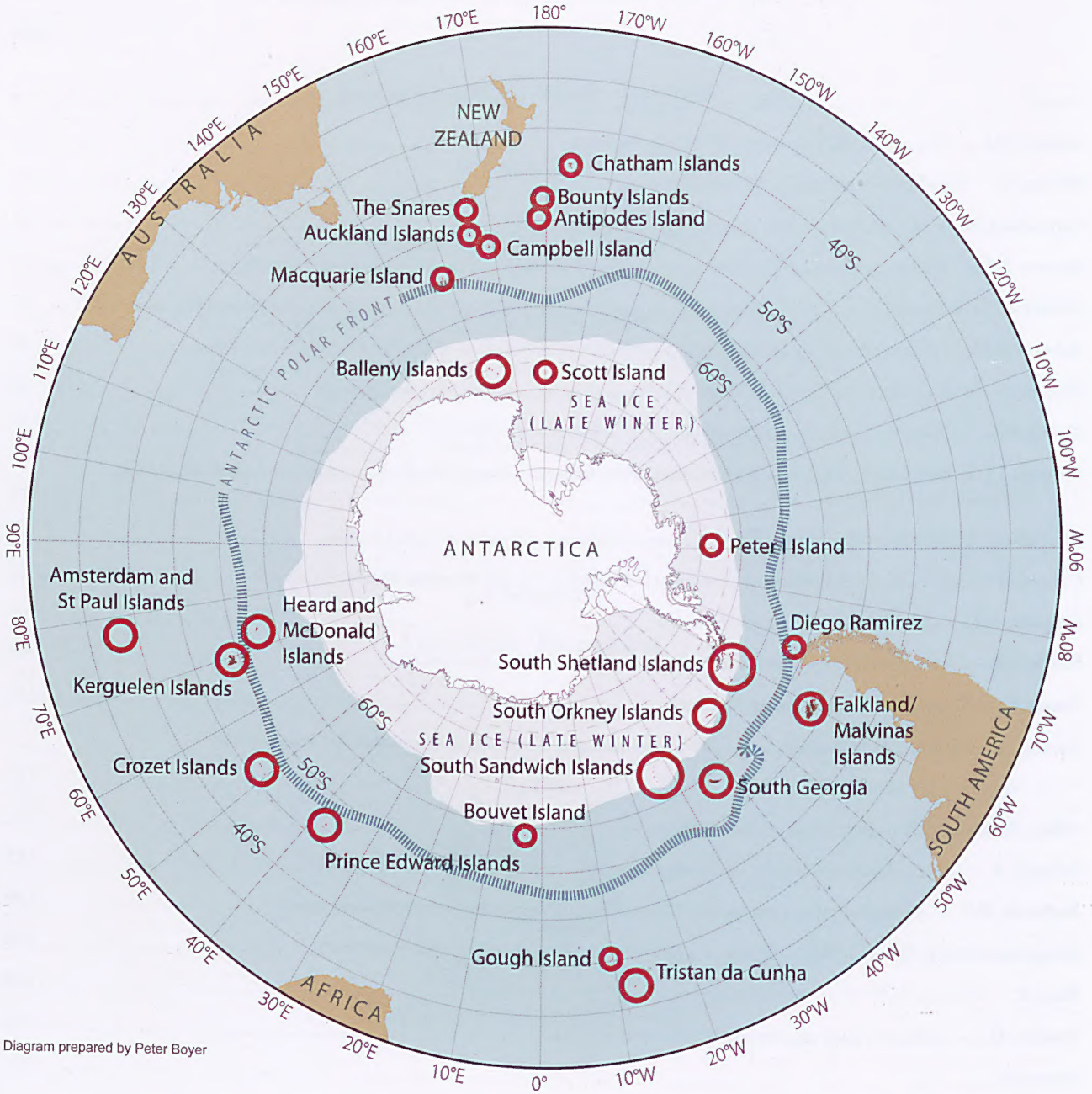


Diagram prepared by Peter Boyer

PREFACE

An International Forum on the sub-Antarctic was held in Hobart, Tasmania on 6–7 July 2006 in the week preceding the Scientific Committee on Antarctic Research (SCAR) Open Science Conference. This is the first time that a meeting has been convened to address solely the science and management in the sub-Antarctic, and this volume, as the proceedings of that meeting, is a unique compilation. Participants were invited to speak as individuals rather than to represent particular national viewpoints, although the various national approaches to management and responsibilities were described and discussed.

No specific definition of the sub-Antarctic was given to participants ahead of the Forum. One clear message from the meeting is that there is no real consensus as to what constitutes the sub-Antarctic but there is a great deal of opinion in common. The area of common interest is vast, including much of the Southern Ocean and its islands, but participants' views differ as to southern and northern limits to the region.

The sub-Antarctic is seldom discussed as a region in its own right, partly because of its administrative diversity. The islands are commonly north of 60°S and thus not covered by the provisions of the Antarctic Treaty (except the few where the provisions of the Convention on the Conservation of Antarctic Marine Living Resources, CCAMLR apply). Management is thus quite different from that applied to Antarctica. The islands are national territories, administered mainly by national Antarctic programs, and are surrounded by territorial waters and Exclusive Economic Zones. The islands are often visited and the ocean crossed by ships *en route* to locations and facilities on the Antarctic mainland, reflecting some aspects of their discovery, as they were found accidentally while expeditions were *in transit* to other known destinations.

Generally the region was explored later than many parts of the world. It is far from the home base of many expeditions (mainly European), and as the islands are so small, their exact locations were not documented until late, leading to some confusion in nomenclature. History has many references to the search for islands that proved to be mythical, such as Nimrod, Royal Company, Dougherty and Emerald islands, perhaps from an erroneous understanding of location or from misidentification of icebergs as islands.

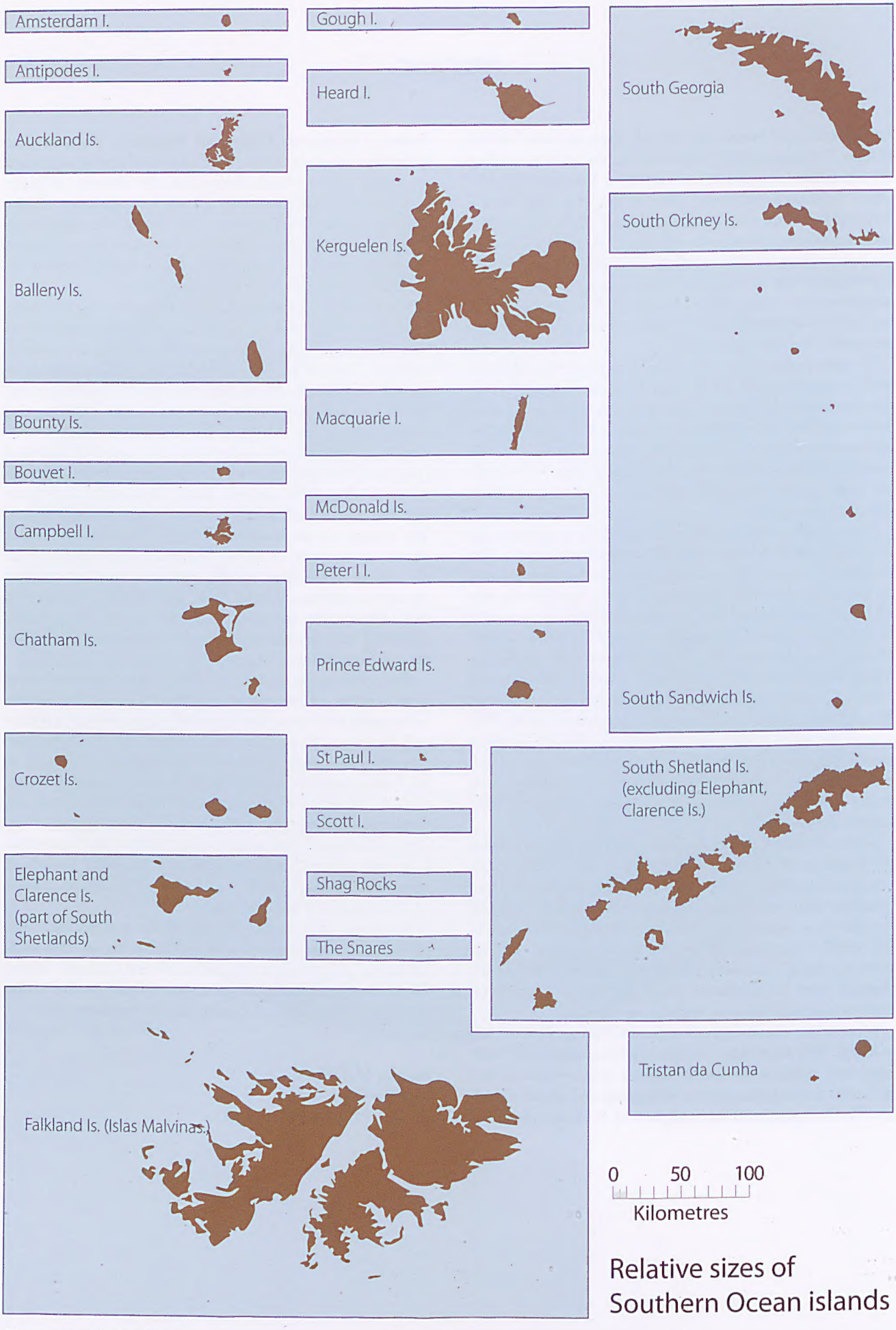
Most of the islands in the Southern Ocean are dominantly volcanic, but most have unique characteristics, and most came into being in the last 20 million years—the later part of Earth's history. In contrast, Macquarie and Heard islands and Îles Kerguelen are exposed parts of the large submarine features (Macquarie Ridge and Kerguelen Plateau) that influence oceanic circulation. While this volume concentrates on details of the islands themselves, the absence of larger landmasses in the Southern Ocean is important. There is little surface interruption (but important submarine influences) to free circulation of the Southern Ocean around the pole-centred southern continent, in marked contrast to the situation in the Northern Hemisphere.

The islands are important biologically as sites for breeding, moulting, resting and the competition between individuals that ensures evolution of fit species. In addition to on-island and near-shore biota, they also have high concentrations of marine vertebrates such as penguins, petrels (in the general sense) and seals that breed and moult ashore. During the mating season the sub-Antarctic islands are noisy, smelly worlds of individual competition for space, mates and reunions. The islands sit in the Southern Ocean, most of which is deep blue marine desert supporting very little life, but the islands lie in a zone of green fertile water. The islands act as a source of iron, fertilising the ocean waters to support extensive marine micro-organisms as the source of all food for the higher trophic levels. The marine vertebrates, during their visits ashore, fertilise the land, transferring nutrients from the sea. At many levels, terrestrial and marine environments are closely linked in the sub-Antarctic.

This publication is in two parts. The first part arises from a series of five-minute presentations at the Forum concerning attributes, management, conservation practices and challenges of particular sub-Antarctic islands. The second part comprises papers arising from longer presentations at the Forum and peer-reviewed in the usual scientific tradition, concerning selected sub-Antarctic topics. We thank all those who helped with organising the meeting and those who participated. The editors are grateful to the many who acted as reviewers for this volume and the Royal Society of Tasmania is pleased to be the facilitator for dissemination of this important compilation.

We hope that publication of these proceedings will promote understanding and appreciation of the sub-Antarctic, and promote discussion of sub-Antarctic issues. We look forward to further meetings to build on the results of the first International Forum on the sub-Antarctic.

Patricia M. Selkirk,
Patrick G. Quilty and
Margaret Davies (co-editors).



Relative sizes of Southern Ocean islands

Diagram prepared by Peter Boyer

THE NATURE AND IMPORTANCE OF THE SUB-ANTARCTIC

by P. M. Selkirk

Selkirk, P.M. 2007 (23:xi): The nature and importance of the sub-Antarctic. *Papers and Proceedings of the Royal Society of Tasmania* 141(1): 1–6. ISSN 0080-4703. Department of Biological Sciences, Macquarie University, Sydney, NSW 2109, Australia.

Sub-Antarctic land is a rare resource in world terms. It is appropriate to recognise the sub-Antarctic as a region distinct from the cool temperate zone to its north and the Antarctic zone to its south, a region with its own characteristics, and with significant intrinsic value and scientific importance. Appropriate protection from anthropogenic change and exploitation must be ensured for the sub-Antarctic.
Key Words: sub-Antarctic, islands, environmental change, anthropogenic change.

NATURE AND LOCATION OF THE SUB-ANTARCTIC

From the vantage point of a plant biologist, the nature and location of the sub-Antarctic is very simple: it is the region south of the south temperate zone and north of the Antarctic zone. The sub-Antarctic is a region of much ocean and little land, a region where herbaceous flowering plants and bryophytes grow well, but where trees and shrubs are absent. It is a region where the tiny specks of land are strongly influenced by the vast ocean and where there are strong connections between marine and terrestrial ecosystems (Smith 1984, Selkirk *et al.* 1990, Erskine *et al.* 1998, Smith *et al.* 2001, Smith 2007).

The sub-Antarctic is a region where temperatures are low and vary little throughout the year (Jacka *et al.* 2004), and where there is abundant moisture. Winter days are short and summer days are long, and although all days are likely to be cloudy (Bureau of Meteorology 2007), there is ample daylight throughout the year, and plant productivity is high (Jenkin & Ashton 1970, Jenkin 1972, Hnatiuk 1979, Smith 1984).

Sub-Antarctic islands, where tussock grasses and lush megaherbs are the tallest plants, contrast very strongly with the cool temperate region to the north, where shrubs or trees are the tallest plants around, forming the dominant vegetation layer. With their oceanic climate, the sub-Antarctic islands contrast equally strongly with continental Antarctica to the south, where temperatures differ markedly between summer and winter (Jacka *et al.* 2004), where daylight and liquid water are available to organisms in the summer but not the winter, where vegetation is dominated by mosses and lichens, growing close to the limits of their physiological tolerance. Just two species of flowering plants, *Deschampsia antarctica* E.Desv. and *Colobanthus quitensis* (Kunth)Bartl., grow in the maritime Antarctic, also at the limits of their physiological tolerance (Smith 1984, Holderegger *et al.* 2003, Robinson *et al.* 2003).

There are different conceptions of what constitutes the sub-Antarctic. Meteorologists define the sub-Antarctic one way (Pendlebury & Barnes-Keoghan 2007), oceanographers another (Ansorge & Lutjeharms 2007). Some confine their idea of the sub-Antarctic to the islands close to the Antarctic Polar Frontal Zone (APFZ); others include a wider range of islands and southern Patagonia. This paper, written by a terrestrial plant biologist, concentrates on the islands of the sub-Antarctic, and particularly the terrestrial biota. However, what is said about the sub-Antarctic will still be pertinent, whatever the reader's circumscription.

By many criteria, the sub-Antarctic is different from other parts of the world. The analogous region in the northern hemisphere is commonly taken to be the vast area of tundra-covered continental land bordering the Arctic Ocean to its north — northern parts of Canada, Greenland, Europe and Siberia, an environment quite different from the ocean-dominated sub-Antarctic (Alexandrova 1980).

It is clear that sub-Antarctic land is a rare resource in world terms, and is discussed here in terms of its importance, distinctive characteristics, intrinsic interest and value.

IMPORTANCE OF THE SUB-ANTARCTIC

The sub-Antarctic region is important as a component of world circulation systems: oceanic systems such as the Antarctic Circumpolar Current (Ansorge & Lutjeharms 2007) and atmospheric circulation such as the Southern Annular Mode (Pendlebury & Barnes-Keoghan 2007).

Sub-Antarctic lands are important to the terrestrial organisms — plants, animals, micro-organisms — that live on the islands, and to the marine mammals and birds that breed there. To humans, the sub-Antarctic is important to scientists — to biologists interested in biogeography, to meteorologists recording land-based data for weather forecasting, to climatologists interested in teleconnections and in climate change, to geologists interested in tectonics and vulcanism, to oceanographers interested in the Southern Ocean — and it is important to the interested tourist visitors now in increasing numbers.

DISTINCTIVE CHARACTERISTICS OF THE SUB-ANTARCTIC

Sub-Antarctic land is entirely made up of small oceanic islands. The islands here considered to be sub-Antarctic all lie close to the APFZ — Macquarie Island, Marion and Prince Edward islands, Crozet Archipelago to the north of the APFZ; Îles Kerguelen within the APFZ; Heard and McDonald islands and South Georgia to the south.

Sub-Antarctic islands have varying geological origins (Quilty 2007), but much in common biologically. They are breeding sites to multitudes of marine mammals and birds that depend on the Southern Ocean for their food, but depend on the sub-Antarctic islands when it comes to their reproduction. Fur seals, elephant seals, albatrosses, prions, petrels, cormorants and other marine birds all are part of the interconnections between marine and terrestrial ecosystems

in the sub-Antarctic: they feed at sea but breed and excrete ashore, transferring nutrients as they do so (Croxall 1984, Laws 1984, Erskine *et al.* 1998, Smith 2007).

The islands are fringed by similar marine algae including dense vegetation of brown algae (Lüning 1990), so that the bull kelp *Durvillaea antarctica* (Chamisso) Hariot could be said to be the dominant plant species of the sub-Antarctic islands (Klemm & Hallam 1988). On the islands vegetation includes tussock grasslands, mires, lakes, fellfields with cushion plants and many bryophytes (Aubert de la Rue 1964, Smith 1988, Duchêne 1989, Selkirk *et al.* 1990, McIntosh & Walton 2000). Terrestrial and freshwater invertebrates found within all these vegetation types include cosmopolitan species as well as characteristically sub-Antarctic ones (Dartnall 2005, Dartnall *et al.* 2005, Chown *et al.* 2006, Greenslade 2006).

Indigenous biota of the sub-Antarctic islands is distinct from that of both the cool temperate and Antarctic regions. A number of species of plants and invertebrates occur on several sub-Antarctic islands but nowhere else in the world: for example, *Pringlea antiscorbutica* R.Br. ex Hook.f., known as Kerguelen cabbage, occurs on Îles Kerguelen, Heard and Marion islands (Telford *et al.* 1993); *Poa kerguelensis* (Hook.f.) Steud., a small tussock grass, is found on Îles Kerguelen and Heard Island (Du Puy *et al.* 1993); *Poa cookii* (Hook.f.) Hook.f., an often larger tussock grass, is found on Îles Kerguelen and Crozet, and Heard, McDonald, Marion, Prince Edward and Macquarie islands (Du Puy *et al.* 1993); the spider *Myro kerguelensis* O.P-Cambridge,1876 occurs on Macquarie and Heard islands, Îles Kerguelen and Crozet (Greenslade 2006).

Some plants and invertebrates are endemic to particular sub-Antarctic islands: for example the small cushion plant *Lyallia kerguelensis* Hook.f. is endemic to Îles Kerguelen (Greene & Walton 1975); the large cushion plant *Azorella macquariensis* Orchard is endemic to Macquarie Island (Orchard 1989); there are two species of orchid, *Nematoceras dienemum* (D.L.Jones) D.L.Jones, M.A.Clem et Molloy and *N. sulcatum* M.A.Clem et D.L.Jones, endemic to Macquarie Island (Jones 1993, Clements & Jones 2007, Clements *et al.* 2007); the waterflea *Daphnia gelida* (Brady, 1918) is endemic to Macquarie Island (Dartnall *et al.* 2005); the flightless moth *Pringleophaga marioni* Viette, 1968 and the weevil *Bothrometopus elongatus* (Jeannel, 1953) are endemic to Marion Island (Barendse & Chown 2001).

The islands are relatively small, relatively young, and have generally evolved in isolation from other landmasses (Quilty 2007). Terrestrial and freshwater organisms have reached the islands by long-distance over-ocean transport — in other words, "via airmail" (Bergstrom & Selkirk 1987, Hennion & Walton 1997, Greenslade *et al.* 1999, Dartnall *et al.* 2005). On-island evolution from an ancestor that arrived by "airmail" is the most likely mechanism for the development of their terrestrial and freshwater endemic species (Clements *et al.* 2007).

INTEREST IN THE SUB-ANTARCTIC

Eighteenth- and nineteenth-century interest in the sub-Antarctic was essentially economic, with the harvesting of marine mammals and birds for economic gain. Seal and penguin populations fell dramatically (Hindell & Burton 1988, McIntosh & Walton 2000), in some places to extinction (Shaughnessy *et al.* 1988). Populations recovered to varying extents after cessation of harvesting and statutory protection of most of the animals in the early to mid-twentieth century.

In the late nineteenth century there was scientific interest in the wildlife of sub-Antarctic islands, and their natural history (Headland 1984, Bryden 1988, Duchêne 1989). By the twentieth century, sufficient scientific knowledge had accrued for some biological harvesting to be sustainably managed, for example elephant seals at South Georgia until the mid-1960s (McIntosh & Walton 2000).

In the twentieth and twenty-first centuries scientific interest has centred on the intrinsic nature of the sub-Antarctic, and studies are working towards an understanding of geological and tectonic processes, ecological and evolutionary processes, and oceanic and upper atmospheric processes. Different islands are of interest to scientists in particular disciplines: for example Macquarie Island is particularly interesting to geologists and geophysicists studying tectonic processes (Varne *et al.* 2000, Goscombe & Everard 2001, Wertz *et al.* 2002, Rivizzigno & Karson 2004); McDonald Island is of particular interest for its recent active vulcanism (Quilty 1995, Kiernan & McConnell 1999); Marion and Heard islands and Îles Kerguelen are of interest to glaciologists, geomorphologists, and biologists studying glacial retreat, its mechanisms and consequences (Scott 1990, Frenot *et al.* 1998, Kiernan & McConnell 1999, Budd 2000, Ruddell 2006).

The sub-Antarctic contains indicators of widespread environmental change, hence is of interest for the observations of change and the interpretation of mechanisms of change. Records from the islands show significant warming over the past 50 years (Thost & Allison 2006, Pendlebury & Barnes-Keoghan 2007), reduced precipitation in some regions and increased windspeed, resulting in somewhat drier conditions, especially in the mires that are significant habitats on sub-Antarctic islands. There has been substantial warming in parts of the Southern Ocean, which is likely to have a flow-around effect on its islands. Glaciers are retreating, new land is becoming ice-free and available for colonisation by organisms already nearby on the islands; there has been reduction in the extent of some species such as *Sphagnum* on Macquarie Island (Whinam & Copson 2006), and an increase in others such as *Acaena* on Heard Island (Scott & Bergstrom 2006). However, there is a great deal not yet known about how organisms will respond to the rapidly changing conditions. Will the colonists of newly deglaciated land all be present residents of the islands? Will the environmental changes allow the establishment of some additional species, yet to arrive by "airmail", or by human-mediated means? Will the changed environment exert different selective pressures on island biota, allowing the evolution of new, endemic species on the islands?

What about the environment itself? For instance, how will geomorphic processes be affected? Periglaciation is the geomorphic process that leads to patterned ground including stone stripes and polygons. Periglacial processes result from freeze-thaw action on unvegetated ground. If temperatures rise so that fewer freeze-thaw cycles occur, periglacial processes may become much more limited in extent, to become restricted to progressively higher parts of the islands where freeze-thaw cycles continue and, ultimately, be inactive in the sub-Antarctic.

On Macquarie Island, peatslides around the steep coastal slopes are triggered by heavy rainfall events. When rain saturates the peat, it becomes unstable and fails when the combined load of vegetation, peat and water becomes too

great for the slope to support (Selkirk 1996). If precipitation decreases and evaporation increases, the incidence of sub-Antarctic peatslides may diminish.

Clearly the sub-Antarctic is a particularly interesting place, one that is interesting to many people, a place that has the capacity to help us understand a number of fundamental processes.

VALUE OF THE SUB-ANTARCTIC

The intrinsic value of the sub-Antarctic islands has formally been recognised in World Heritage listing for Macquarie Island, Heard Island and the McDonald Islands, and the New Zealand shelf islands, and in the tentative World Heritage listing of Marion and Prince Edward islands.

In the past, the sub-Antarctic had commercial value for its exploitable biota — the myriad seals and penguins whose skins clothed many people, and whose oil lit many houses. Now there is monetary value in tourism, and potentially in future for other purposes, such as the development of sub-Antarctic plants as vegetable or horticultural crops (Dawson 1998), or sub-Antarctic microbiota as sources for biotechnology developments.

The risk of damage to the sub-Antarctic should not be overlooked. There is risk of damage to sub-Antarctic islands from alien plants, specifically those that become invasive. Many such plants have arrived on sub-Antarctic islands as hitchhikers on humans and their equipment, from soon after the islands were discovered, through the era of seal and penguin and whale exploitation, through settlement and farming practices, to the present era of scientific investigation and tourism (Whinam *et al.* 2004, Frenot *et al.* 2005, Convey *et al.* 2006, Bergstrom & Selkirk 2007). Similarly, alien animals that become feral pose threats to sub-Antarctic environments. Some, such as mice and rats, travelled on ships and went ashore uninvited; others, such as cats, rabbits and reindeer, were imported for a purpose at a time when the threats they would later pose were not appreciated (Leader-Williams 1988, Convey *et al.* 2006). Recovery programs have achieved the eradication of cats from Marion Island (Bester *et al.* 2002), of weka and cats from Macquarie Island (Copson 1995, 2003), of rabbits and rats from Île Saint Paul and from three small islands in the Îles Kerguelen (Lebouvier & Frenot 2007), and of rats from Campbell Island (McClelland & Tyree 2004, Shepherd 2007). Quarantine measures aim to prevent further introductions (Copson & Whinam 2001, Whinam *et al.* 2006), and management practices are in place for the control of some of the alien species now present (Copson & Whinam 2001, Courchamp *et al.* 2003, Cooke *et al.* 2004). On Macquarie Island, however, management of the feral rabbit population has become ineffective, with deleterious consequences for bird populations and vegetation (Considine 2007, Parks and Wildlife Service 2007). A plan for the eradication of rabbits and rodents has been developed (Parks and Wildlife Service 2007), funding from the Australian and Tasmanian governments has been approved, and the plan is expected to be implemented over the years 2007 to 2012.

Other threats of damage to sub-Antarctic islands come from anthropogenic pollution damage including fuel leaks and waste dumping (Stark *et al.* 2003). Hydrocarbon spills are considered to be more damaging in cold than in warmer climates, and ecosystem recovery slower (Snape *et al.* in press). Surveys and toxicity testing have shown the need for remediation in some locations (Stark *et al.* 2003, Schafer *et al.* in press, Rayner *et al.* in press). Considerable quantities of derelict building materials have been removed from Heard Island during several clean-up operations (Stark *et al.* 2003, Hull 2002) and plans are in train for remediation at sites on Macquarie Island (Raymond *et al.* 2005). The oil spill associated with the 1987 foundering of M.V. *Nella Dan* killed invertebrates and adversely affected the littoral and sub-littoral environment over several kilometres of Macquarie Island's shoreline for more than a year (Pople *et al.* 1990). Marine plastic rubbish, often dumped thousands of kilometres away, damages birds and seals both at sea and on beaches when washed ashore (Slip & Burton 1991).

There is potential for change in the sub-Antarctic. Climate change, including rising temperatures and falling precipitation, and resultant environmental change including retreating glaciers, have been considered above. These changes in the physical environment will be associated with biological changes; there is the potential for additional biota to arrive naturally and to become established, independent of human agency; and there is the capacity for new biota to evolve.

It is clear that all change is not a bad thing, to be resisted: the world has been a changing place throughout its existence and continues to change. The sub-Antarctic is no exception — Macquarie Island continues to rise as tectonic plates move (Adamson *et al.* 1996), McDonald Island continues to expand following recent volcanic eruptions (Australian Antarctic Division 2005).

It is appropriate to ponder, with better knowledge and understanding than in the past, whether the sub-Antarctic is adequately protected from deleterious exploitation, and indeed from deleterious anthropogenic change, of any nature.

CONCLUSION

I believe that the sub-Antarctic, however defined, must be recognised as a region in its own right, distinct from the Antarctic region to its south and from the cool temperate region to its north. It is time to move away from the long-standing tendency for the sub-Antarctic to be regarded as "not the real Antarctic", or "less than the Antarctic".

The characteristics, intrinsic value and scientific importance of the sub-Antarctic must be recognised, and appropriate protection from deleterious anthropogenic change and exploitation ensured. Humans, as custodians of the planet, must recognise and value the unique qualities of, and must care for all parts of, the Earth, including the sub-Antarctic.

ACKNOWLEDGEMENTS

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HEARD ISLAND AND MCDONALD ISLANDS

by Ewan McIvor

(with two text-figures)

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The sub-Antarctic Heard Island and McDonald Islands (HIMI) group is an Australian external territory located in the Indian Ocean sector of the Southern Ocean. The island group was inscribed on the World Heritage list in 1997 for its outstanding natural universal values, primarily due to the relative absence of human influence on the natural environment. The Territory also forms part of a 65 000 km² Marine Reserve, declared under the *Environment Protection and Biodiversity Conservation Act 1999* in 2002 to protect the conservation values of the islands and the surrounding unique and vulnerable marine ecosystems. The Territory and Marine Reserve are managed by the Australian Antarctic Division of the Department of Environment and Water Resources, in accordance with the Heard Island and McDonald Islands Marine Reserve Management Plan 2005, which aims to address a range of potential human pressures, most notably the risk of introduced species.

Key Words: sub-Antarctic islands, Heard Island, McDonald Islands.

LOCATION AND PHYSICAL CHARACTERISTICS

The Heard Island and the McDonald Islands (HIMI) group is located in the Indian Ocean sector of the Southern Ocean at approximately 53°S 73°30'E, some 4000 km southwest of Western Australia, 4700 km southeast of Africa and 1000 km north of the Antarctic continent. The nearest land is the French territory of Îles Kerguelen, approximately 440 km to the northwest (fig. 1). Together, these island groups form the only surface exposures of the Kerguelen Plateau, one of the world's largest submarine plateaux.

Heard Island is approximately 43 km long from the tip of the Laurens Peninsula in the northwest to the tip of Elephant Spit in the southeast, and covers an area of approximately 368 km² (see fig. 2). The landforms on Heard Island have been sculpted by the interaction of diverse processes, including a long and complex geological history (Quilty 2007), multiple episodes of volcanic activity, erosion and transport by wind, water and glaciers, moulding by vigorous marine processes and the influence of gravity (Kiernan & McConnell 1999).

Heard Island is dominated by Big Ben, a heavily glaciated and roughly circular volcano with a base diameter of 18–20 km and maximum elevation of 2745 m (Quilty & Wheller 2000). Due to its height and location south of the Antarctic Convergence, approximately 70% (or 257 km²) of the island is covered by glaciers and a further 2% by year-round snow (Ruddell 2006). There are 12 major glaciers radiating towards the sea from the summit of Big Ben or from the peaks of Laurens Peninsula (Ruddell 2006). As a result of regional warming the extent of the glaciers is decreasing, with corresponding development, expansion and coalescing of coastal lagoons and ice-free areas (Kiernan & McConnell 2002).

Numerous minor eruptions and other volcanic events, such as plumes, have been observed on Big Ben since 1947 (Quilty & Wheller 2000). Recent volcanic activity has dramatically altered the McDonald Islands, located approximately 40 km to the west. Sometime during the 1990s, the main island doubled in size — to approximately 2.5 km² — and became joined via a low-lying isthmus to the previously separate Flat Island (Quilty 2007).

The climate is strongly influenced by the islands' location south of the Antarctic Convergence in a zone of strong and persistent westerly winds — the "furious 50s" — and by local factors, such as the perennial ice cover and mountainous nature of Heard Island. The maritime setting leads to low seasonal and daily temperature ranges, persistent and generally low cloud cover, frequent precipitation and strong winds. Records from Atlas Cove, near sea level at the northwestern end of the island, show a monthly average temperature range from 0.0–4.2°C, monthly average wind speeds of 26–33.5 km/hr and annual precipitation of 1.3–1.9 m (water equivalent) (Thost & Allison 2006).

HISTORY

Due to the isolation and persistently severe weather and sea conditions, human activity has been, and remains, limited. Although sealing activity had been under way at Îles Kerguelen since the 1770s, the first confirmed sighting of Heard Island was made only in 1853 by Captain John Heard on the *Oriental*, with the McDonald Islands sighted the following year by Captain William McDonald on the *Samarang* (Downes & Downes 2006).

The first landing at Heard Island was by a sealing expedition in February 1855, and over 40 vessels made more than 100 voyages to the island in the following three decades seeking oil from Southern Elephant Seals *Mirounga leonina* (Linnaeus, 1758) (Downes & Downes 2006). Brief visits were also made by whalers and sealers in the early 1900s. Some evidence of these early activities remains, with items such as stone platforms, hut ruins, oil barrels and graves still present at several coastal sites (McGowan & Lazer 1989, McGowan 2000, Hughes & Lazer 2000).

Several brief scientific visits to Heard Island were conducted by expeditions from several nations in the late nineteenth and early twentieth centuries, but the first extensive scientific studies occurred during the operation of the Australian National Antarctic Research Expedition (ANARE) station at Atlas Cove between December 1947 and March 1955. As with the sealing-era artefacts, the remains of the ANARE station are included in Australia's Register of the National Estate for their historic importance.

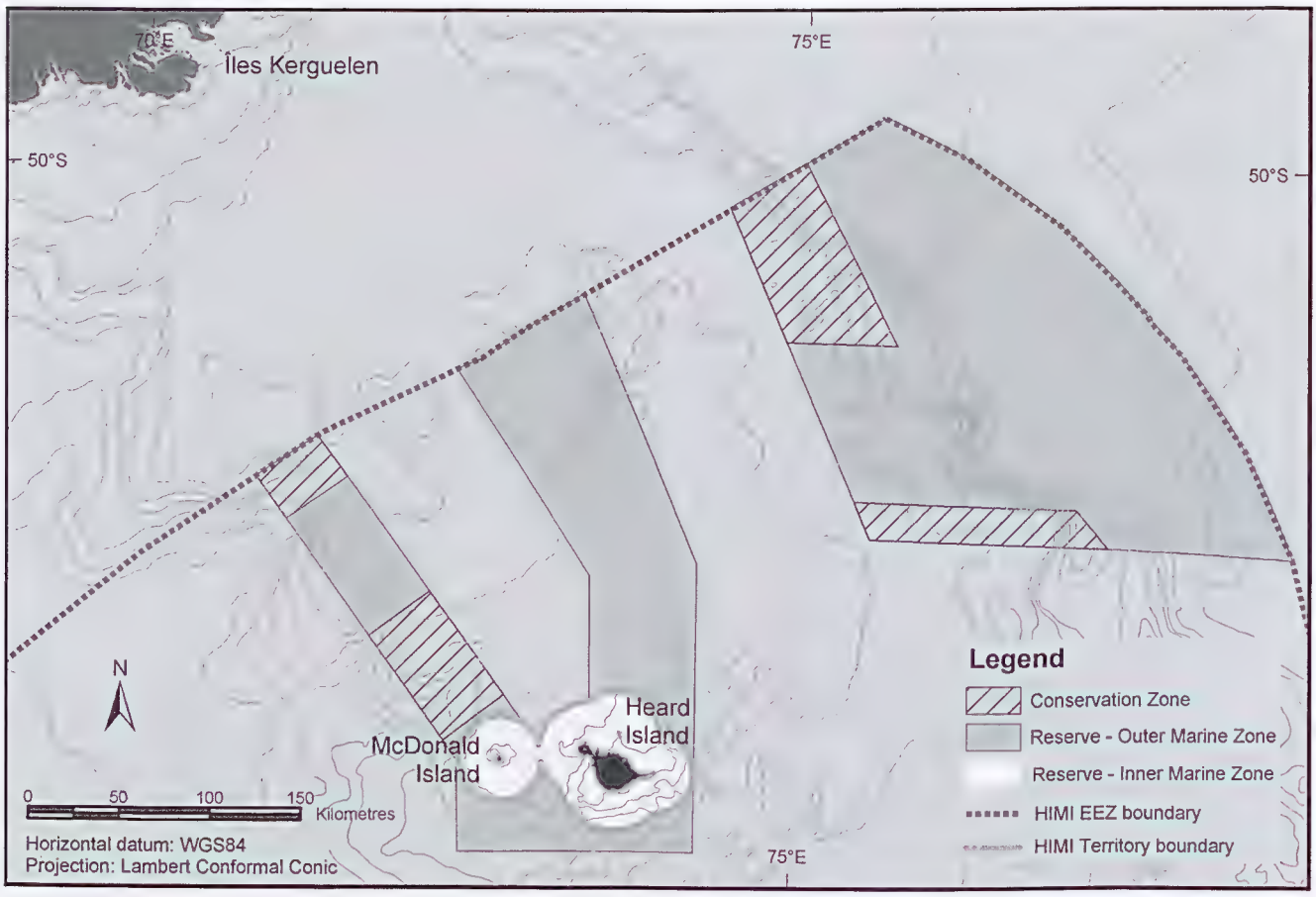

FIG. 1 — Heard Island and McDonald Islands Marine Reserve boundaries.

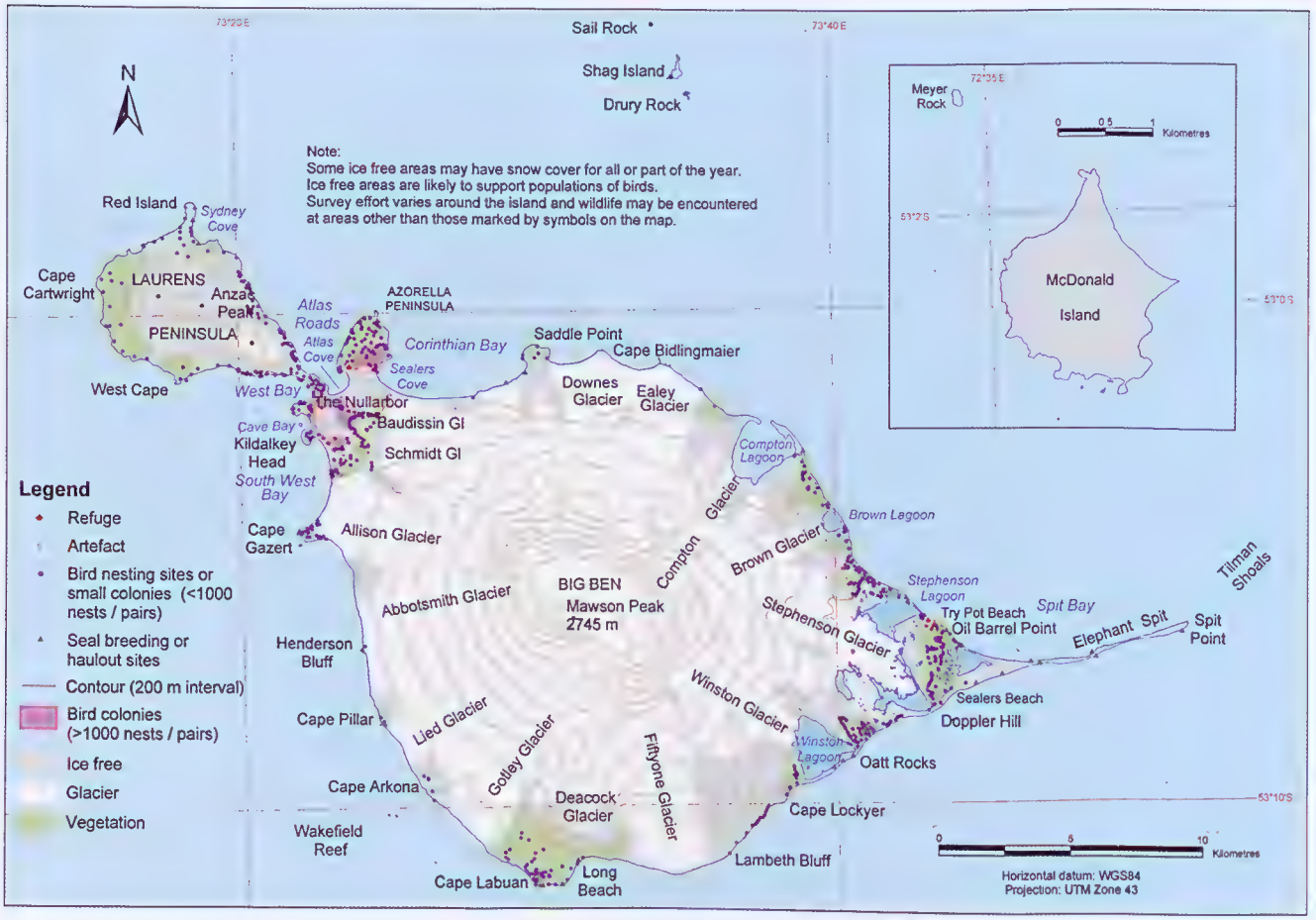

FIG. 2 — General map of Heard Island and McDonald Islands.

Periodic Australian research expeditions have been made to Heard Island since the Australian ANARE station was closed in 1955, and occasional visits have also been made by other nations. There are only two brief recorded landings at McDonald Island, in 1971 and 1980. The high cost and substantial logistical requirements for visits to HIMI have meant that private expeditions and commercial tourist visits have been infrequent and brief.

Terrestrial and marine research, as part of the Australian Antarctic science program, is currently the main human activity at Heard Island and research expeditions are mounted every few years. However, commercial fishing in the adjacent waters is the most frequent human activity in the region.

FLORA AND FAUNA

The relatively late discovery of the islands, combined with minimal human visitation over the twentieth century, mean that the flora and fauna has recently been subjected to minimal impact by local human activities. Importantly, Heard Island is the largest sub-Antarctic island with no known human-introduced plant species or vertebrate predators.

The terrestrial flora is typically sub-Antarctic, with low-growing herbaceous flowering plants and bryophytes comprising the major components of the vegetation. Substantial vegetation covers almost 20 km^2 of Heard Island, mostly in coastal areas at elevations below 250 m (Scott & Bergstrom 2006, Scott & Ryan 2004). With 12 vascular plant species on Heard Island (and only five of these recorded from McDonald Island) (Jenkin 1987), HIMI has the lowest number of vascular plant species of any major sub-Antarctic island group (Scott & Bergstrom 2006).

Non-vascular plants contribute substantially to the overall biodiversity of Heard Island, with 62 recorded species of bryophyte and 71 recorded species of lichen (Scott & Bergstrom 2006). With climate warming and increasing availability of new ice-free habitat, some plant species are spreading and modifying vegetation communities, some of which are also increasing in distribution. Seven vegetation communities are currently recognised: open-cushionfield vegetation — characterised by *Azorella selago* Hook.f. cushions interspersed with bryophytes, small vascular species and bare ground — being the most widespread and abundant (Scott & Bergstrom 2006; Bergstrom *et al.* 2002). A survey at McDonald Island in 1980 found fewer communities than Heard Island (Jenkin 1997), and recent volcanic activity will have altered the vegetation.

Fifteen species of seabird have been recorded as breeding on Heard Island (Woehler & Croxall 1991), including two endemic species (Heard Island Cormorant *Phalacrocorax atriceps* (King, 1828) and Heard Island Sheathbill *Chionis minor nasiconis* Reichenow, 1984), four listed threatened species (Southern Giant Petrel *Macronectes gianteus* (Gmelin, 1789), the aforementioned Heard Island Cormorant, Antarctic Tern *Sterna vittata* Gmelin, 1789, and Wandering Albatross *Diomeda exulans* Linnaeus, 1758). Penguins are by far the most abundant birds, and four breeding species are present, including two listed threatened species (Macaroni *Eudyptes chrysolophus* (Brandt, 1837) and Rockhopper *Eudyptes chrysocome* (Forster, 1781)). Volcanic activity at McDonald Island may have affected bird populations, but earlier surveys estimated Macaroni Penguin populations on Heard and McDonald Islands as approximately two million birds each (Woehler & Croxall 1991).

Three breeding seal species are recorded, including two listed threatened species (Southern Elephant Seal *Mirounga leonina* and Sub-Antarctic Fur Seal *Arctocephalus tropicalis* (Gray, 1872)). Relative to other Southern Ocean islands, Heard Island supports a low number of terrestrial invertebrate species (Chown *et al.* 2006).

Heard Island has a number of small wetland sites scattered around its coastal perimeter, including areas of wetland vegetation, lagoons, pool complexes, rugged rocky shores, sandy shores and the Elephant Spit. Many of these wetland areas are currently separated by glaciers. Wetlands have also been recorded on McDonald Island but, following recent volcanic activity, their present extent is unknown.

MARINE ENVIRONMENT

The waters surrounding the islands contain important and unique benthic species and assemblages, representative portions of the different habitat types in the region, nursery grounds for commercial fish species, and near-surface waters where land-based marine predators concentrate their local foraging activities. These special qualities were recognised in the declaration of the HIMI Marine Reserve in 2002 which, at 65 000 km^2, is one of the largest marine protected areas in the world.

CONSERVATION AND MANAGEMENT

The enactment of legislation and the implementation of measures to ensure formal protection of the conservation values of the HIMI Territory and surrounding region have been a priority since Australia assumed responsibility for administration and management in 1947. The *Heard Island and McDonald Islands Act 1953* made provisions for the protection of wildlife and the making of ordinances for the administration of the islands, and the *Environment Protection and Management Ordinance 1987* (EPMO) made under the Act established a legal regime for the protection of indigenous plants and animals, including the obligation to prepare a management plan for the Territory and the requirement for a permit to enter or undertake activities in the Territory. The Heard Island Wilderness Reserve Management Plan was made under the EPMO and came into effect in 1996. The management plan provided priorities for decisions that would affect the Territory, defined appropriate uses and activities, outlined management areas and contained management strategies for protecting the Territory's values.

In 1998 the HIMI region was identified in Australia's Oceans Policy (Commonwealth of Australia 1998) as one of five areas where the Australian Government would preferentially pursue a marine park, to ensure Australia's temperate and sub-Antarctic waters were incorporated in the comprehensive and representative system of marine protected areas and to help protect Australia's unique marine biodiversity. The HIMI Marine Reserve was declared under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) in October 2002 for the purpose of "*protecting the conservation values of Heard Island and McDonald Islands and the adjacent unique and vulnerable marine ecosystems*".

The Marine Reserve includes the islands and surrounding territorial sea (the HIMI Territory) plus additional marine areas extending in parts to the exclusive economic zone

(EEZ) boundary. It is designated as an IUCN category Ia strict nature reserve, to be managed primarily for science and environmental monitoring. The management objectives include:

- protecting conservation values of HIMI, the territorial sea and the adjacent EEZ including:
  - the World Heritage and cultural values of the HIMI Territory
  - the unique features of the benthic and pelagic environments
  - representative portions of the different marine habitat types
  - marine areas used by land-based marine predators for local foraging activities.
- providing an effective conservation framework which will contribute to the integrated and ecologically sustainable management of the HIMI region as a whole
- providing a scientific reference area for the study of ecosystem function within the HIMI region
- adding representative examples of the HIMI EEZ to the National Representative System of Marine Protected Areas.

The HIMI Territory and Marine Reserve are managed by the Australian Antarctic Division (AAD) of the Australian Government Department of the Environment and Water Resources, in accordance with the Heard Island and McDonald Islands Marine Reserve Management Plan (Australian Antarctic Division 2005).

The management plan addresses legal requirements arising from both the EPBC Act and the EPMO, action plans for a range of threatened species and numerous applicable international agreements, including the World Heritage Convention, Ramsar (wetlands) Convention, Bonn (migratory species) Convention, bilateral migratory birds agreements with China and Japan, and the Agreement on the Conservation of Albatrosses and Petrels.

It incorporates strict measures to minimise the risk of introducing non-native species, to avoid disturbance to the flora and fauna, and to prevent adverse impacts of waste and pollution. It also recognises the important contribution that scientific research at HIMI can make to understanding the effects of climate change, and to sustainably managing the surrounding marine environment. It obliges humans to act as "thoughtful, responsible and privileged visitors", requires adherence to an environmental code of conduct for visitors, and defines a suite of management zones to facilitate protection of areas that are susceptible to the impacts of human activities — such as vegetated areas, listed threatened species and sensitive geological features — and to confine human activity to sites that can sustain it.

Fishing is prohibited within the Marine Reserve, but an Australian commercial fishery operates in other areas within the HIMI EEZ. The fishery falls within the area of application of the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) and is managed in accordance with the Heard Island and McDonald Islands Fishery Management Plan 2002 by the Australian Fisheries Management Authority (AFMA).

Other Australian Government agencies with management responsibility for activities in the HIMI region include the Australian Customs Service and Australian Defence Force, which are responsible for border protection and security, and the Australian Maritime Safety Authority, which is responsible for shipping and marine safety.

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MACQUARIE ISLAND, ITS CONSERVATION AND MANAGEMENT

by N. Carmichael

Carmichael, N. 2007 (23:xi): Macquarie Island, its conservation and management. *Papers and Proceedings of the Royal Society of Tasmania* 141(1): 11–17. ISSN 0080-4703. Parks and Wildlife Service, P.O. Box 126, Moonah, Tasmania 7009, Australia.

Sub-Antarctic Macquarie Island, 12 785 ha in area, is part of the Australian state of Tasmania. It is managed by the Tasmanian Parks and Wildlife Service, in cooperation with the Australian Department of the Environment and Water Resources, as a World Heritage Area, Nature Reserve, Biosphere Reserve and National Estate property. The reserve encompasses outstanding and unique geological values, exceptional natural beauty, abundant wildlife and internationally significant historic heritage. The island is surrounded by the Macquarie Island Marine Park of 16 200 000 ha. This paper outlines frameworks for the conservation and management of its biota and environment including its unique geology.

Key Words: sub-Antarctic, Macquarie Island, conservation, management, World Heritage Area.

LOCATION AND PHYSICAL CHARACTERISTICS

Macquarie Island is located approximately 1500 km from Hobart at 158°55'E, 54°30'S, roughly halfway between Tasmania and Antarctica (fig. 1). Its nearest neighbours are the New Zealand islands of Auckland and Campbell. The island is nearly 34 km long, up to 5 km wide and has a terrestrial area of 12 785 ha. An undulating plateau of between 150 and 300 m high forms the backbone of the island, whilst Macquarie's highest point, Mt Hamilton, reaches 433 m (Parks and Wildlife Service 2006).

Macquarie Island is located just north of the Antarctic Polar Frontal Zone and has a climate best described as cool, wet and windy, with a mean air temperature of 3.3°C in winter and 7.0°C in summer. The mean annual precipitation of 920 mm is spread over about 312 days and there are on average 268 days of strong winds annually (Parks and Wildlife Service 2006).

Macquarie Island is geologically unique, being the only island composed entirely of oceanic crust, with all rocks having been formed on or beneath the ocean floor. The island is the only exposed section of the Macquarie Ridge, which stretches from around 61°S as far north as New Zealand (Selkirk *et al.* 1990, Parks and Wildlife Service 1999). The seafloor on the eastern side of the island drops steeply to the Macquarie trench at a depth of over 5500 m, whilst the western side slopes somewhat less steeply to a depth of approximately 3500 m (Parks and Wildlife Service 1999).

The island emerged approximately 600 000–700 000 years ago and its numerous raised beach deposits (marking palaeoshorelines) provide graphic evidence of the island's uplift, which has been estimated to be approximately 0.8 mm per year (Adamson *et al.* 1996). The northern part of the island has rock outcrops which illustrate the unique exposure of rocks from the upper mantle (about 6 km below the ocean floor), whereas the southern three-quarters of the island is composed mainly of basalt rocks, such as the extensive pillow lavas which formed on the ocean floor (Parks and Wildlife Service 1999).

FLORA AND FAUNA

Macquarie Island has no trees or shrubs, but has 47 species of vascular flora, four of which are endemic (including two orchids) (Clements *et al.* 2007). There are generally considered to be five major vegetation formations: tall tussock, short grassland, herbfield, mire and feldmark (Selkirk *et al.* 1990). Only five alien plant species have been recorded in the reserve in recent years (Copson & Whinam 2001).

In common with most other sub-Antarctic islands, Macquarie Island supports a vertebrate fauna of low diversity but high abundance. Amongst the most common species are: Light-mantled Sooty Albatross *Phoebetria palpebrata* (Forster, 1785) (1500 breeding pairs); Southern Elephant Seals *Mirounga leonina* (Linnaeus, 1758) (approximately 80 000); King Penguins *Aptenodytes patagonicus* Miller, 1778 (approximately 170 000 breeding pairs); the endemic Royal Penguin *Eudyptes schlegeli* Finsch, 1876 (approximately 850 000 breeding pairs); and three species of Fur Seal *Arctocephalus* spp. (several hundred) (Scott 1994, Parks and Wildlife Service 2006). The reserve also protects a number of rare or threatened species, including 16 fauna species and one plant species that are listed under the Tasmanian *Threatened Species Protection Act 1995*.

HISTORY

Macquarie Island was discovered by sealing parties in 1810 and the island's abundant fur seals, elephant seals, (and later) penguins, were subsequently all heavily exploited. Scientific expeditions followed, most notably Sir Douglas Mawson's Australasian Antarctic Expedition which operated a scientific station on the island between 1911 and 1914. Commercial exploitation of the island's wildlife ceased in 1919 (Cumpston 1968).

The Australian Antarctic Division (AAD) has operated a scientific station at the Isthmus since 1948, and approximately 14–25 people are based on the island each year. The station supports research in space and atmospheric physics, meteorology, human biology and medicine, biology, and geosciences.

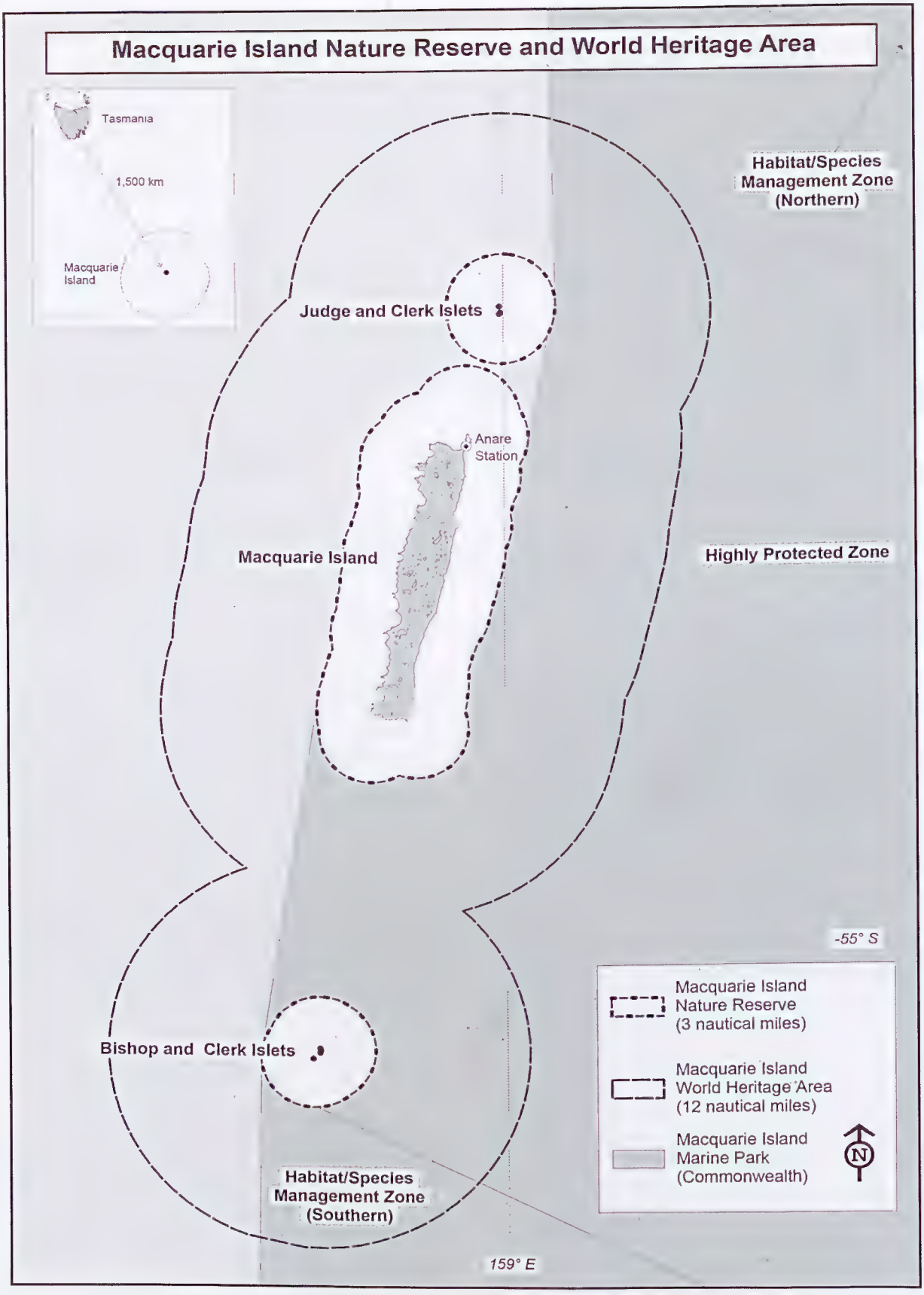

FIG. 1 — Macquarie Island Nature Reserve and World Heritage Area. Reproduced with permission from the Tasmanian PWS.

CONSERVATION AND MANAGEMENT

Reserve status and tenure

Macquarie Island enjoys the very highest levels of national and international protection. It was declared a Wildlife Sanctuary in 1933 and given its current status as a Nature Reserve in 1978. Macquarie Island Nature Reserve covers the island, outlying islets (Judge and Clerk islets and Bishop and Clerk islets), and surrounding state waters out to three nautical miles (nm), resulting in a total area of 87 500 ha.

The island, islets and surrounding waters out to 12 nm were inscribed as a World Heritage Area in 1997, largely based on their outstanding geoheritage and natural beauty values (Parks and Wildlife Service 2006). In addition, Macquarie Island is a Biosphere Reserve; a National Estate property; and has Critical Habitat values under the *Environment Protection & Biodiversity Conservation Act 1999*. Most of the ocean on the eastern side of the island out to 200 nm is encompassed by the Macquarie Island Marine Park, the second largest Marine Protected Area in the world with an area of approximately 16 200 000 ha. The Marine Park supports a highly protected zone and two habitat species management zones (Department of the Environment and Water Resources 2007).

Management framework

Macquarie Island Nature Reserve is part of the Australian state of Tasmania and is managed by the Tasmanian Parks and Wildlife Service (PWS). The PWS and the Australian Department of the Environment and Water Resources have cooperative management arrangements for the World Heritage Area and the Macquarie Island Marine Park. The AAD has generously supported PWS management of the reserve over many years and all PWS staff on the island go there as part of the Australian Antarctic Program.

A new management plan was proclaimed in 2006 and will provide management direction for the reserve for at least the next seven years. The plan has established three management zones in order to regulate infrastructure levels and manage the impacts of human activities in the reserve. Zone A (Services Zone) covers the area around the Australian Antarctic Division scientific station, Zone B (Limited Access Zone) covers the remainder of the island, and Zone C (State Marine Waters) encompasses the marine area (fig. 2).

All scientific programs on Macquarie Island require a permit, and as the reserve has been declared a restricted area under the *National Parks and Reserved Land Regulations 1999*, all visitors must have an access authority to enter. Special Management Areas (fig. 3) have also been established around the coastline to regulate access by Australian Antarctic Program expeditioners to sensitive parts of the reserve during the breeding seasons of vulnerable wildlife species such as seals, albatross and penguins.

Introduced vertebrate pests

In common with most sub-Antarctic islands, Macquarie has had a number of accidentally or deliberately introduced vertebrate pest species which have adversely affected reserve values (De Villiers *et al.* 2006). These include: Weka *Gallirallus australis scotti* (Ogilvie-Grant, 1905) (eradicated in 1989); Feral Cats *Felis catus* Linnaeus, 1758 (eradicated in 2000); European Rabbits *Oryctolagus cuniculus* (Linnaeus, 1758); House Mice *Mus musculus* Linnaeus, 1758; and Ship Rats *Rattus rattus* Linnaeus, 1758.

Rabbits and rodents are currently significantly impacting on the island's native flora and fauna. Some of the species (together with their designation under either Australian or Tasmanian threatened species legislation) most threatened by this impact are: Grey Petrels *Procellaria cinerea* Gmelin, 1789 (Endangered); Black-browed Albatross *Diomedea melanophrys* Temminck, 1828 (Endangered); Blue Petrels *Halobaena caerulea* (Gmelin, 1789) (Vulnerable); and White-headed Petrels *Pterodroma lessonii* (Garnot, 1826) (Vulnerable).

Rabbits change vegetation communities through grazing, whilst rodents can prey upon the eggs and chicks of small seabirds as well as affect invertebrate communities and impact on the recruitment of plants (Copson 1986, Shaw *et al.* 2005). The dominant coastal vegetation type on Macquarie is tall tussock *Poa foliosa* (Hook .f.) Hook. f. Once tussock has been lost to rabbit grazing, landslips start to occur and species unpalatable to rabbits (such as mosses) dominate the slope. Tussock loss has adverse micro-climatic effects on seabird burrows (less dark, colder, drier and less wind protection) and also reduces protection from native predators such as skuas *Catharacta lonnbergi* (Mathews, 1912) (Threatened Species Unit 2004). Rabbits also indirectly impact upon burrow-nesting seabirds by allowing an inflated skua population to exist, thereby increasing skua predation pressure (Jones & Skira 1977, Skira 1984). The island skua population is currently at the highest level recorded.

Rabbit numbers have increased significantly recently as a result of resistance to myxoma virus, removal of cats as a predator and possible island warming. In response to such rabbit and rodent impacts, a combined Rabbit and Rodent Eradication Plan for the island was developed in consultation with international experts (Parks & Wildlife Service 2007). The eradication plan proposes using helicopters to conduct an intensive aerial baiting program over the whole island. The plan envisages that all rats and mice should be killed by the bait drops, but that some rabbits are likely to survive. Consequently a multi-year on-ground phase using hunting teams and dogs is also planned in order to mop up any surviving rabbits.

Surveys undertaken by PWS in 2005, 2006 and 2007 have revealed that most of the island's coastal slopes have now suffered over 50% rabbit grazing damage. In recognition of the severity of the feral animal problem on Macquarie, the Australian and Tasmanian governments agreed in mid-2007 to jointly fund the eradication plan. A lengthy preparation period for the eradication program has now commenced, during which all of the necessary environmental and safety approvals, in addition to the major logistical groundwork required will be undertaken. The Macquarie Island Rabbit and Rodent Eradication Plan will be the largest and most ambitious sub-Antarctic island eradication ever undertaken.

Tourism

Although a Nature Reserve, educational tourism is allowed under the management plan. This has been limited to

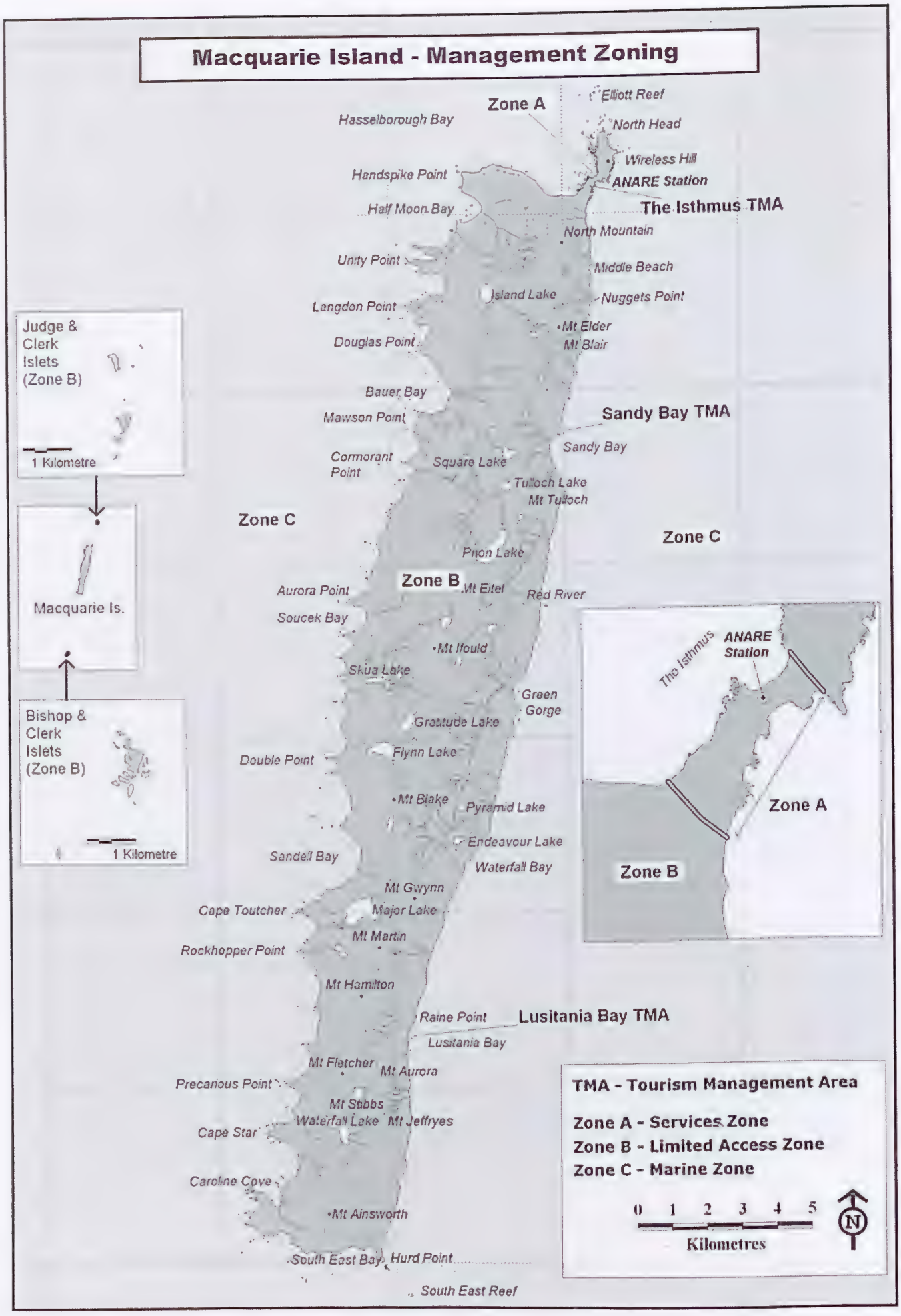

FIG. 2 — Macquarie Island Management Zoning. Reproduced with permission from the Tasmanian PWS.

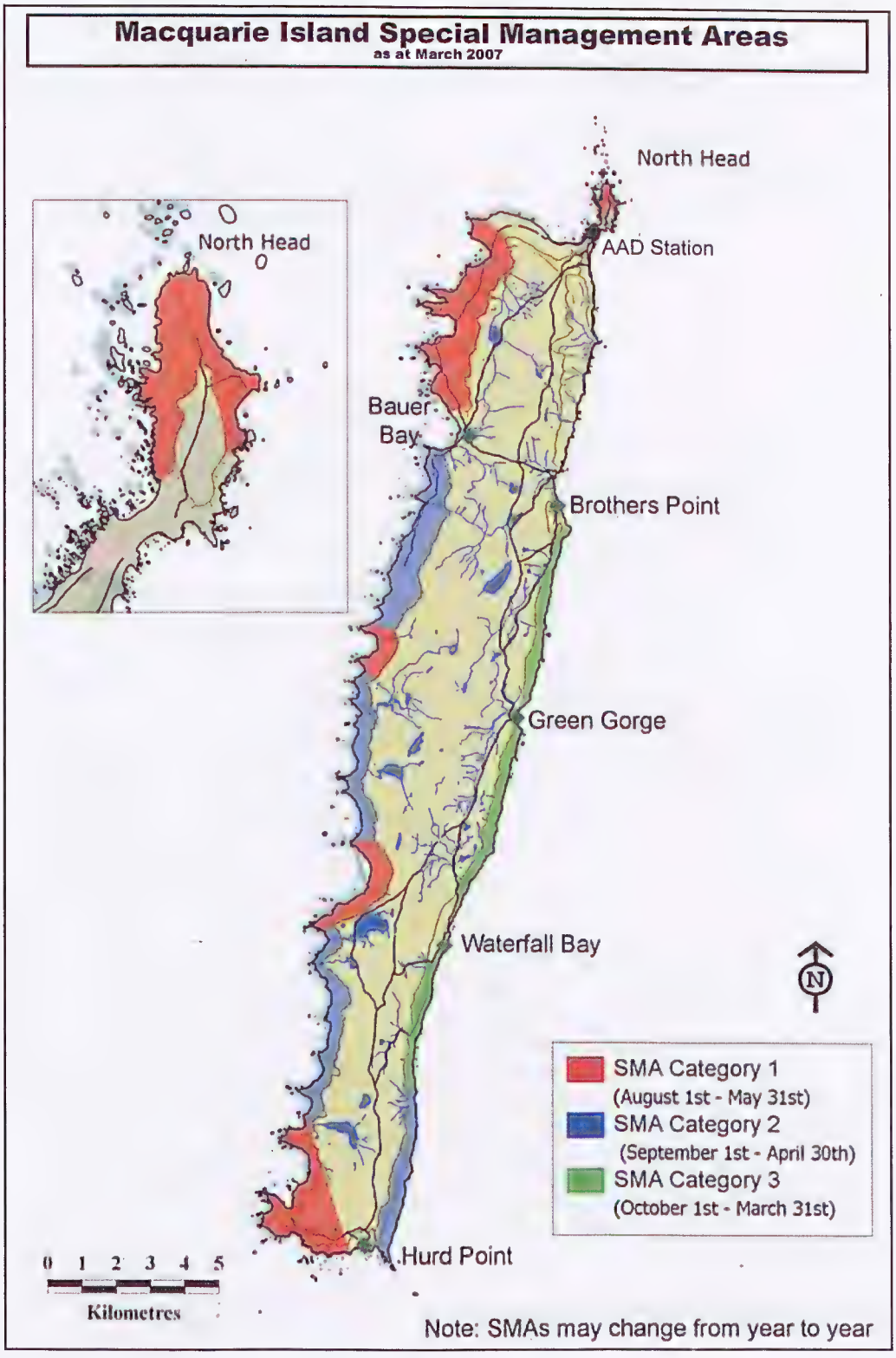

FIG. 3 — Macquarie Island Special Management Areas. Reproduced with permission from the Tasmanian PWS.

around six to eight tourist ships visiting the island each summer, which have been landing between 300 and 500 passengers since regular commercial visits began in 1990. Visit applications are assessed against a range of environmental, safety and economic criteria. A large increase in visitation was experienced over the 2005–2006 season, however, and interest in visits to the island appears to be increasing. All tourist visits are ship-based (for a maximum of two days each) and closely supervised by PWS and AAD staff. Three Tourism Management Areas have been designated in order to regulate access, with tourists generally being restricted to the beaches and specially constructed boardwalks at the Isthmus and Sandy Bay in addition to being allowed to Zodiac cruise off Lusitania Bay.

Quarantine

Quarantine is likely to remain the most important long-term management issue for the island. In recognition of this, the AAD and PWS have developed a comprehensive quarantine management program for the island under which pre-departure and on-arrival measures are strictly enforced, and all introductions are logged and investigated (Whinam *et al.* 2005). Enforcing an ongoing rigorous quarantine regime for Macquarie will be even more important once rabbits and rodents have been eradicated. In addition, managing the increasing levels of visitation to the island (such as educational tourism), will probably require more proactive measures (such as addressing the threat of introduced marine pests) and greater resources in order to maintain an acceptable level of risk over the long-term (Lewis *et al.* 2006). The increased levels of communication and cooperation in the field of sub-Antarctic island management in recent years is a very welcome development which should yield benefits for tourism and quarantine management.

Historic heritage

Macquarie Island has internationally significant historic heritage with outstanding examples of early steam digester technology at several sites, such as Hurd Point and the Nuggets (Nash 2003). Many of these down-island sites, however, are degrading rapidly due to weathering, storms and wildlife disturbance. A large collection of movable historic artefacts located at the scientific station also needs ongoing conservation management (Clark 2003). The rapid rate of change at many sites provides only a limited window of opportunity for active management to be successful. Considerable resources will be required to properly address the long-term management of historic heritage sites and artefacts on the island.

SUMMARY OF MANAGEMENT ISSUES

The most important and pressing management issue is that of vertebrate pest control and eradication. The island is currently experiencing unprecedented levels of rabbit grazing damage, resulting in severe impacts on reserve values and threatened seabird species. An ambitious rabbit and rodent eradication plan has been developed and has recently been funded. The continued degradation of Macquarie Island's internationally significant historic heritage sites is also an issue that needs to be addressed in the very near future, before too much more of the resource is lost. Finally, the increased interest in educational tourism may also result in increased environmental risk, particularly from a quarantine perspective.

ACKNOWLEDGEMENTS

The successful management of Macquarie Island would be impossible without the ongoing cooperation and support of many other agencies and individuals. In particular, thanks must go to the Australian Antarctic Division for its generous support for Tasmanian Parks and Wildlife Service management programs on Macquarie Island; to the Australian Department of the Environment and Water Resources; and to staff from the Tasmanian Department of Primary Industries and Water.

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MARINE CONSERVATION AND MANAGEMENT AT SOUTH GEORGIA AND THE SOUTH SANDWICH ISLANDS

by L. F. Sahores

Sahores, L.F. 2007 (23:xi): Marine conservation and management at South Georgia and the South Sandwich Islands. *Papers and Proceedings of the Royal Society of Tasmania* 141(1): 19–22. ISSN 0080-4703. Consulado General de Argentina, Level 20, 44 Market Street, Sydney, NSW 2000, Australia.

South Georgia and the South Sandwich archipelagoes fall within the scope of SCAR (Scientific Committee on Antarctic Research) and CCAMLR (Convention for the Conservation of Antarctic Marine Living Resources). From the early twentieth century to the present Argentina has proposed and supported international agreements and conventions to regulate the harvesting of marine biota, and to promote marine conservation. Adherence to CCAMLR is required by Argentine law.

Key Words: sub-Antarctic, South Georgia, South Sandwich Islands, marine conservation, fisheries management, CCAMLR Convention.

The South Georgia and South Sandwich archipelagoes are sub-Antarctic islands that fall within the scope of SCAR (Scientific Committee on Antarctic Research).

Conservation of the environment for future generations as an obligation of the present is part of all cultures and has been evident in many social, legal and religious institutions. Nowadays conservation is a principle, unchallenged and universally accepted, in spite of the fact that, in practice, participants might deviate from it due to short-term considerations. Regulation of these short-term considerations is seen by Argentina as the basis for management and is at the core of our legislation. However, a description of the conservation and management framework requires an understanding of the developing nature of the regulatory body.

In 1812 a new method of processing seal skins was introduced in pelt factories increasing commercial interest in southern sealing. Despite efforts to regulate catches, Patagonian seals were depleted below commercial levels by 1825.

In 1913 Chile proposed a Convention, to be agreed by Argentina, Brazil and Uruguay, to jointly regulate hunting and fishing in the southern seas. The impossibility of including the long-distance operators in this Convention meant that adherence to the Convention would act "against the signatories and to the benefit of the non-adhering".

In April 1924, the Argentine Secretary for cattle production, remarkable jurist and economist Dr José León Suárez presented to the League of Nations through its Committee of Experts for the Progressive Codification of International Law a proposal for the immediate establishment of uniform regulations for the exploitation of maritime industries. He suggested convening a Commission of Experts (from all interested governments) to draft such regulations through "successive consultations" (Suárez 1925).

The League of Nations Committee of Experts charged Dr Suárez to analyse and report back on "the feasibility of establishing, by international agreement, rules about the exploitation of marine riches", taking into account existing treaties and other international instruments. In preparing his report, Dr Suárez consulted with experts from several countries, and identified the main issues under discussion at that time. His report of the appalling situation and future of the marine resources was presented to the Committee in December 1925. In January 1926, it was presented — together with the Committee's recommendation on the urgent nature of the decisions to be made — to the Council of the League of Nations. Enshrined in this report is the idea that measures had to be taken with a view to imposing regulations on the free take of natural resources which had resulted in an open race, ignoring long term considerations (Suárez 1925).

The report also recognised the wider and long-term consequences of unregulated exploitation: "... particularly in the maritime fauna the biological solidarity, considered jointly within all species, is more effective than in the terrestrial fauna, the disappearance of some will cause an unbalance in their harmonies and fights for existence and the extinction of others". As early as 1926, it was accepted that conservation is an ecosystem issue that must be dealt with in an international and multidisciplinary frame.

In his report Dr Suárez clearly identified the issues involved in the regulation of the exploitation of marine resources. These were later formalised, described and modelled:

- The lack of international regulation will lead marine species to extinction.
- There is a growing need for food resources, in particular marine resources.
- The extinction of one species entails the risk of loss of balance in the ecosystem and the extinction of other species.
- Most species are migratory, with a distribution pattern that varies geographically and from year to year.
- The absence of international regulation pushes commercial companies to over-capitalise in order to take the largest possible share of a dwindling resource.
- Technological improvements break the balance between production and consumption of marine species.
- The authority derived from the existence of maritime jurisdictions (three miles at the time, which might be expanded) — is not enough to provide the type of regulatory frame needed.
- There is a need for the uniform regulation of "sea industries" which are "a food reserve of mankind", especially in the continental shelves and in Antarctic waters.
- There is a need to determine the most efficient method to survey and control the application of international regulations.
- Existing treaties are insufficient and could, at best, only

delay the final extinction of resources. Most of these treaties might well represent an additional risk as not only they are limited both in membership and scope but also exclusively take into account "commercial interests and political reciprocities", thus leaving aside the "biological interest", a concept that is not separable from the "general economic interest".

- While the undeniable need to establish international regulation for the exploitation of the biological riches of the sea is new to jurists, the need is recognised by all who have an interest (scientific or commercial) in marine fauna.
- It is prudent to establish a technical commission with membership open to all interested governments. Within such a commission, the views of lawyers, scientists and the industry should be considered in the establishment of international regulations.

From 1931 onwards, whaling became a highly regulated operation but regulations were unable to prevent the further decline of the whale stocks.

The international developments in fisheries regulation followed the path of partial agreements, applying to a large number of fisheries agreements covering high seas and shared resources (limited to seals and whales in the southern seas) and the expansion of the jurisdiction and responsibilities of coastal states into maritime zones.

By the mid-1970s the problems of over-exploitation of demersal fish around the South Georgia islands were evident: after a period of rapid expansion in the 1960s and early 1970s catches had substantially declined. This, together with the growing interest of the fishing industry in krill (*Euphausia superba* Dana, 1850), prompted the convening of a technical conference in 1976.

The conference considered it difficult to provide for the rational administration of fisheries on the basis of the Antarctic Treaty alone. As already recognised in Dr Suárez's report, fishing agreements cannot ensure conservation objectives. Political and economic considerations will pervade deliberations and eventually result in the depletion of stocks as seen in most of the world's fisheries. The conference highlighted the need for a specific legal, political and scientific framework within which measures could be developed and implemented.

In 1977 the Antarctic Treaty Consultative Meeting initiated a negotiating process which resulted in the adoption of the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) in 1980 (CCAMLR 2005).

Argentina participated actively and welcomed the inception of the CCAMLR Convention, since CCAMLR elaborated and consolidated many of the principles and concepts that had evolved during the previous 50–60 years; many of them can be traced back to the discussions in the League of Nations. This evolution has made CCAMLR an influential body developing many of the current ideas in the field of conservation. Besides these proactive characteristics it is also unique in that, as a part in the Antarctic Treaty System (ATS), it cannot act as the "owner" of the resources; it does not intend to optimise exploitation and it cannot generate fishing rights.

The theoretical approaches applied in the analyses of fishing strategies postulate that resources are either owned or open access. CCAMLR is a counterexample that proves that the dilemma is false: it is regarded as more advanced and more successful than most Regional Fisheries Management Organisations (RFMOs) and national administrations, without applying the tools derived from the existence of exclusive rights of access to the resources. CCAMLR established a geographical area following the concept of biological and oceanographic unity, and proposed the application of a uniform set of rules for the whole area, to "give effect to the objectives and principles set out in Article II of this Convention". To this end, the Commission "shall take full account of the recommendations and advice of the Scientific Committee".

CCAMLR's objectives spelt out completely and accurately those principles, giving also a basis for operational definitions, particularly Article II. These are as follows:

- Conservation applies not only to the resources, but is extended to the ecosystem as a whole.
- Conservation includes "rational", and not "optimal" use. In RFMOs' practice and in theoretical analyses of fisheries, optimal refers to the maximisation of economic benefits. Conservation as defined by the Convention is limited by the need to contribute to food security.
- Reference points are established, effectively ensuring conservation, independently of the discount rates used by different participants (Maximum Sustainable Yield and minimisation of the risk of changes).
- Restoration of populations depleted below those reference points is required.
- The rule of the special responsibility of the Flag State is included as a part of the system as — according to the Convention — the responsibility for investigating and sanctioning remains in the Flag State.
- The basic elements to be included in a system of international observation directed to "promote the objective and ensure observance of the provisions of this Convention", are established, thus effectively providing for boarding vessels in the high seas.

The principles include cooperation between Contracting Parties to implement the system; boarding and inspection by observers and inspectors designated by Members; procedures for Flag State prosecution and sanction and reporting the results to the Commission;. targeting scientific research or harvesting vessels; designation by Members of observers and inspectors and reporting to the Members; and distinguishing two components in Members' contributions to the annual budget: a part defined on an equal sharing basis and a part calculated from the amount of living resources harvested.

Within CCAMLR, compliance and data collection fall within the responsibility of Flag States with the cooperation of all Members. Carrying an observer on board has become a standard requirement for vessels operating in the CCAMLR area, except for the krill fishery. In many instances a second observer is also included in the provisions of the relevant Conservation Measures (in general practice he or she is designated by the Flag State).

By its very nature, inspection creates a suite of legal and practical problems. The right of an inspector from any country to board a fishing or scientific research vessel in the CCAMLR area implied that the Flag State has to resign, at least to some extent, its authority over the vessel involved. This feat was achieved through an elaborate mechanism.

The inspector, while a national of the designating country, is not an inspector of that country but a "CCAMLR inspector designated by XX". Clear identification of this status is required and it is provided by a special document issued by the designating country in a CCAMLR-approved form. The vessel carrying a CCAMLR inspector must fly a CCAMLR-designed pennant and clearly inform the

inspected vessel of the inspector's name (a special registry of designated inspectors is kept by the CCAMLR Secretariat) and its intention to inspect the vessel under the CCAMLR system of inspection.

The Convention provides its Parties with a mechanism for cooperation among different and even opposing legal systems, as long as the *status quo* is not modified. Smooth cooperation among countries at loggerheads both at global and local levels was made possible.

In this framework, the Chairman's Statement allows, under special circumstances, such as their pre-existence, the application of regulations based on ownership of the resources and always biased to the side of conservation.

Non-discrimination between Parties on any basis (e.g., history of catches, scientific efforts, etc.) makes CCAMLR provisions easily acceptable and internally legitimate for Parties and non-Parties.

In this way, CCAMLR's regulations are universally accepted because they are founded on incontrovertible principles. For example, the Catch Documentation Scheme has not been challenged in spite of the fact that it might be viewed as an unfair commercial practice which discriminates against some countries.

Thus, the CCAMLR conservation and management framework, founded on multilateral cooperation and Flag State responsibility, is not only fully applicable to the South Georgia and South Sandwich islands from a legal point of view but is also sound and effective enough to achieve the conservation objectives.

Argentina endorsed the CCAMLR Convention, contributed to the work of the Commission and Scientific Committee and developed its national legislation regarding its sub-Antarctic islands convinced that the appropriate management and conservation framework is the full application of the multilateral approach developed by CCAMLR. This approach is widely regarded as the most advanced conservation scheme for marine resources and its viability has been demonstrated.

The main Argentine legal instrument is Law 25263 (2000). Its main provisions are:

- definition of competences (Article 1)
- achievement of the objectives of the Convention (Article 2)
- recognition of the legal status of CCAMLR's regulations without delay (Article 3)
- definition of procedural matters regarding fishing within CCAMLR waters (Articles 4–8, 13–15 and 35–40)
- creation of the CCAMLR fund (Articles 9–11)
- obligation to carry a VMS in CCAMLR waters, at all times and without exceptions (Articles 16–18)
- sanctions for infringements (Articles 19–33)
- obligation to unload in Argentine ports (Article 34)
- reports from CCAMLR Observers and Inspectors, including sightings have legal standing (Article 41)
- provisions for research, scientific observation and inspection (Articles 42–45).

Within Argentinean national legislation, violation of CCAMLR's provisions — by Argentine-flagged vessels — is regarded as a serious infringement attracting heavier fines than those applied to similar situations outside the Convention area.

Argentina also applied in full the CCAMLR observation and inspection schemes, carried out port inspections and supported CCAMLR in all ways.

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CONSERVATION AND MANAGEMENT IN THE FRENCH SUB-ANTARCTIC ISLANDS AND SURROUNDING SEAS

by M. Lebouvier and Y. Frenot

(with two text-figures and one table)

Lebouvier, M & Frenot, Y. 2007 (23:xi). Conservation and management in the French sub-Antarctic islands and surrounding seas. *Papers and Proceedings of the Royal Society of Tasmania* 141(1): 23–28. ISSN 0080-4703. Ecobio, Université de Rennes 1, CNRS, Station Biologique, 35380 Paimpont, France (ML*); Institut Polaire Français Paul Emile Victor, BP 75, 29280 Plouzané, France (YF). *Author for correspondence.

Of the French islands in the Southern Indian Ocean, Archipel Crozet and Îles Kerguelen are considered sub-Antarctic, and Île Amsterdam and Île Saint-Paul temperate. All have endemic species amongst their biota. The Terres Australes et Antarctiques Françaises (TAAF) is responsible for sovereignty of these islands, the French Polar Institute (IPEV) is the central agency for research, and the Committee for the Polar Environment (CEP) provides advice on environmental protection and management issues. In 2006 all of the islands gained the status of Nature Reserve, and a management plan is expected to be in place within three years, providing greater protection for the environment and biota.

Key Words: sub-Antarctic islands, Archipel Crozet, Îles Kerguelen, Île Saint-Paul, Île Amsterdam.

Among the French islands located in the Southern Indian Ocean, two groups are really sub-Antarctic — Archipel Crozet, north of the Polar Front, and Îles Kerguelen, close to the Polar Front — whereas Île Amsterdam and Île Saint-Paul lie north of the subtropical convergence.

ARCHIPEL CROZET

Location and physical characteristics

Archipel Crozet consists of five main oceanic islands, Île aux Cochons, Île des Pingouins, Îlots des Apôtres, Île de la Possession and Île de l'Est (table 1 and fig. 1). These mountainous islands, entirely volcanic in origin, are split into two groups, western and eastern, 100 km apart. This archipelago has been built by several magmatic events which started 10 million years ago. Rocks are volcanic and plutonic in the eastern group, and volcanic in the western group (Giret *et al.* 2003).

The climate is oceanic, cold and windy: mean annual air temperature is 5.3°C with monthly mean temperatures ranging between 3.2°C in winter and 8.1°C in summer; total annual precipitation is around 2400 mm; strong west winds are frequent. No permanent ice exists today but past glaciations have occurred as evidenced by large glacial valleys on Île de l'Est and Île de la Possession

History

After their discovery in 1772 by Marion-Dufresne these islands were visited by sealers and whalers in the nineteenth century. The Alfred Faure permanent scientific and meteorological station (130 m a.s.l), was built in 1963–64 on the eastern coast of Île de la Possession. A small transitory population, around 40 people in summer and 25 people in winter, is present on this station.

Flora and fauna

Herbaceous vegetation occurs at low altitude. Above 150 m a.s.l. feldmark vegetation dominates. Twenty-four native vascular plant species have been recorded at Île de la Possession. Most of the flora belongs to the Southern Indian Ocean biogeographical province and there is no plant species endemic to the archipelago. Fifty-eight alien plant species have been

TABLE 1
Physical variables for each island of Archipel Crozet

	Position	Area, km²	Altitude, m	Age, myr
Western group				
Île aux Cochons	46°05'S–50°15'E	68.3	843	0.4–0.2
Île des Pingouins	46°25'S–50°24'E	5.6	340	1.1
Îlots des Apôtres	45°58'S–50°26'E	3.4	292	5.5–2.6
Eastern group				
Île de la Possession	46°25'S–51°45'E	147.1	934	8.1
Île de l'Est	46°25'S–52°15'E	129.8	1090	8.7

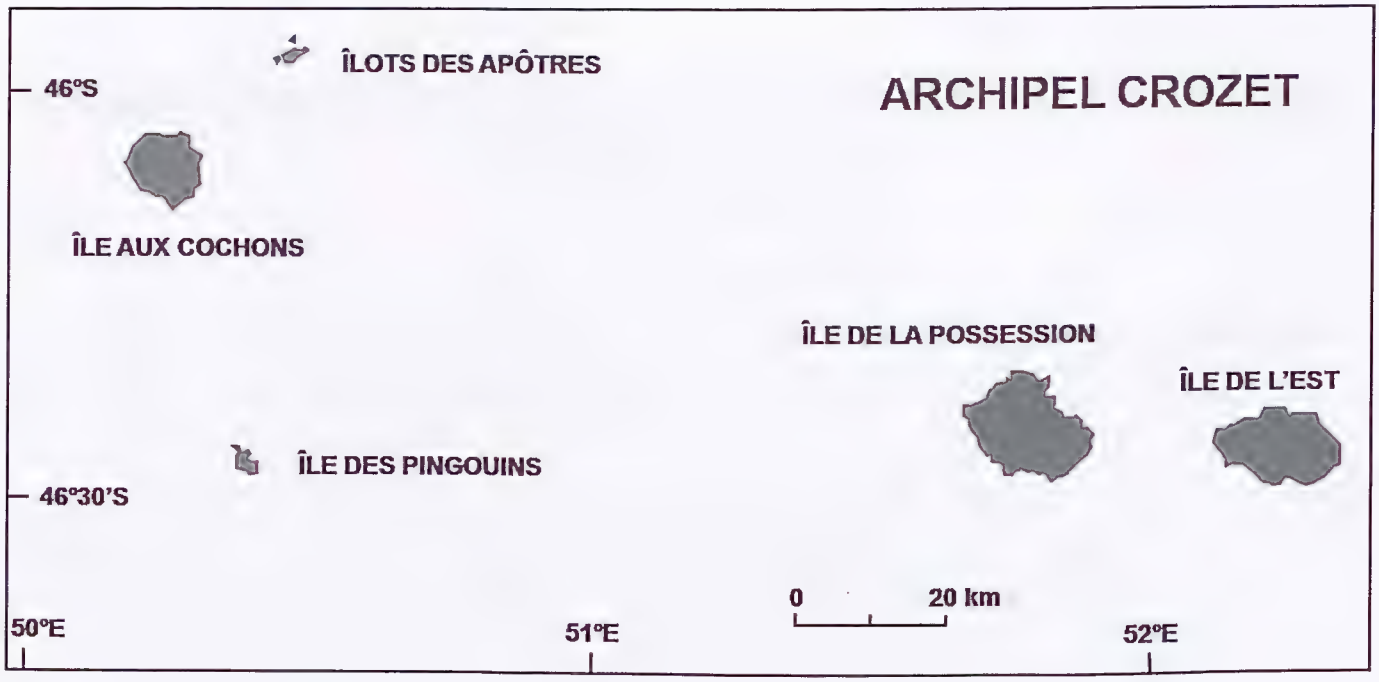

FIG. 1 — General map of Archipel Crozet.

recorded at Île de la Possession. These species are localised around the Alfred Faure station with only seven species widely distributed over the island (Frenot *et al.* 2001).

The invertebrate fauna is characterised by a high level of endemism, especially for Diptera and Coleoptera. Alien invertebrates are few (14 species) and most are only present in the vicinity of the research station (Frenot *et al.* 2005).

Thirty-six species of seabirds breed in the archipelago. Île aux Cochons supports the largest King Penguin colony in the world with about 300 000 pairs (Jouventin *et al.* 1984).

Five alien mammal species are present in the archipelago: the black rat *Rattus rattus* Linnaeus, 1758 on Île de la Possession, the rabbit *Oryctolagus cuniculus* (Linnaeus, 1758) on Île de l'Est and Île aux Cochons, the house mouse *Mus musculus* Linnaeus, 1758 and the cat *Felis catus* Linnaeus, 1758 on Île aux Cochons (Chapuis *et al.* 1994). Cats and rats greatly reduce the numbers of breeding seabirds.

ÎLES KERGUELEN

Location and physical characteristics

Îles Kerguelen lie between 48°30' and 50°S, and 68°27' and 70°35'E. This wide archipelago (7200 km²) consists of a main island (6500 km²), surrounded by dozens of smaller islands and numerous islets. The coastline is deeply indented, with numerous fjords and, in the eastern part of the archipelago, a wide and relatively sheltered bay, Golfe du Morbihan. High mountains, several glaciers and an icecap (Calotte glaciaire Cook) occur in the western part of the main island. The highest point (Mont Ross) is 1850 m a.s.l.

These volcanic islands have developed over a very long period (the oldest rocks are around 30 Ma). Many characteristic and unusual features in their geological history led Giret *et al.* (1997) to consider Îles Kerguelen as a "third type of oceanic island". Hot springs in some places attest to a present volcanic activity.

The climate is oceanic and cold with strong westerly winds all year round. At Port-aux-Français station, in the eastern part of the main island, the mean annual air temperature is 4.6°C with monthly mean temperatures ranging between 2.0°C in July and 7.7°C in February; total annual precipitation is around 760 mm (Météo-France 1951–2005 records). However, rainfall is higher, up to 3500 mm/yr, in the western part of the archipelago. Climate has changed markedly over the past few decades (Frenot *et al.* 1997). The mean annual air temperature has increased by 1.3°C since the mid-1960s and the mean annual rainfall has decreased by 150 mm over the past 10 years at Port-aux-Français (Chapuis *et al.* 2004).

History

After their discovery in 1772 by Kerguelen these islands were regularly visited by sealers and whalers in the late eighteenth and early nineteenth centuries, and subsequently, by several scientific expeditions, notably by expeditions to observe the transit of Venus in 1874. A whaling station was established in 1908 and worked intermittently until 1930. In 1913 an attempt to farm sheep, imported from the Falkland Islands, was unsuccessful (Arnaud & Beurois 1996). The scientific and meteorological station, Port-aux-Français, was established in 1951 and has been permanently occupied since that date by a small transitory population of around 100 people in summer and 50 people in winter.

Flora and fauna

Twenty-nine native vascular plant species (22 phanerogam and seven pteridophyte) have been recorded at Îles Kerguelen. Most of the flora belongs to the Southern Indian Ocean biogeographic province and the only endemic species is *Lyallia kerguelensis* Hook. f. which is closely related to *Hectorella caespitosa* Hook. f. (Portulacaceae) of New Zealand (Wagstaff

& Hennion 2007). Amongst the 68 alien plant species recorded at Îles Kerguelen, 49 are present around the station at Port-aux-Français while seven invasive species are widely distributed within the archipelago (Frenot *et al.* 2001).

The total number of introduced and naturalised invertebrate species is high (30), compared with the numbers in other sub-Antarctic islands (Frenot *et al.* 2005). Amongst 39 insect species currently found at Îles Kerguelen 23 are endemic or sub-Antarctic and 16 are alien (Schermann-Legionnet *et al.* 2007).

The avifauna is rich and diverse, with 35 breeding bird species (Weimerskirch *et al.* 1989).

Amongst the marine mammals, Southern Elephant Seals *Mirounga leonina* (Linnaeus, 1758) and Antarctic Fur Seals *Arctocephalus gazella* (Peters, 1875) breed at Îles Kerguelen. Their numbers have rebounded since the cessation in sealing.

Five salmonid fish and seven alien mammal species are present, having been introduced intentionally or unintentionally; they include black rats, rabbits, mice, cats, reindeer *Rangifer tarandus* Linnaeus, 1758, sheep *Ovis aries* Linnaeus, 1758 and Corsican mouflon *Ovis musimon* Pallas, 1762 (Chapuis *et al.* 1994).

The impact of the introduced mammals on the structure and functioning of the ecosystem is dramatic. Rabbits, present on many islands and widely distributed on Grande Terre, have greatly reduced the plant species diversity. For instance, the sub-Antarctic *Acaena magellanica* (Lam.) Vahl (Rosaceae) now occupies wide areas as nearly monospecific heathlands. In order to rehabilitate islands degraded by rabbits and to study the recovery of native plant communities a program of eradication by poisoning was implemented on three small islands from 1992 onwards (Chapuis *et al.* 2001). By the early 2000s rats had been eradicated on three small islands by conservation programs. Cats were introduced in 1956 to control rats and mice at Port-aux-Français station. Their number and range have increased very quickly and a control program of shooting in the mid-1970s failed. Cats are responsible for the destruction of thousands of burrowing birds, mainly small petrels every year (Weimerskirch *et al.* 1989). Sheep and mouflon are currently present on two islands in Golfe du Morbihan, Île Longue and Île Haute respectively. After the introduction of 10 animals in 1956, reindeer have colonised a wide part of Grande Terre but the present size and distribution of the population are poorly known.

ÎLE AMSTERDAM AND ÎLE SAINT-PAUL

Location and physical characteristics

Île Amsterdam (37°50'S, 77°30'E) and Île Saint-Paul (38°43'S, 77°31'E) are very isolated islands located halfway between South Africa and Australia, close to the East Indian mid-oceanic ridge. Palaeomagnetic data suggest that the main part of Île Amsterdam arose during the period 400–200 kyr BP. However, numerous recent volcanic cones can be seen and the youngest was probably formed during the nineteenth century (Giret 1987). Île Amsterdam is elliptical in shape, about 9.2 km long by 7.4 km wide and 55 km² in land area. The entire coastline, except for two locations in the northwest, is surrounded by steep cliffs, commonly 30–60 m high, rising up to 700 m in the western part, where the highest cliffs have been caused by a geological subsidence of a part of the volcano. The northern, eastern and southern slopes are concentric around an old caldera, le Plateau central, at 720 m a.s.l., which is dominated by the highest point, Mont de la Dives, peaking at 881 m a.s.l. Plateau des Tourbières is a large flat area between this high point and the western cliffs.

Île Saint-Paul, 80 km south of Île Amsterdam, is more recent than Île Amsterdam. Hot springs and fumarolic gas are still observed. Île Saint-Paul is a small crescent-shaped collapsed crater. A central lake crater with a diameter of 1000 m is open to the ocean and accessible to small boats by a narrow channel, 0.8–2.5 m in depth depending on the tide. The land area is 7 km² and the highest point is 265 m a.s.l.

Due to its location north of the subtropical convergence the climate of Île Amsterdam is oceanic and mild. Strong westerly winds are frequent, especially in winter. The mean air temperature is 14.0°C (11.2°C in August, 17.4°C in February). Cloudiness is high all year round and the mean annual rainfall at the meteorological station (27 m a.s.l.) is around 1100 mm distributed over 226 days; a dry period occurs in summer.

History

Île Amsterdam was discovered in 1522 by Sebastian del Cano, on one of Magellan's ships, on the way back to Europe after the first circumnavigation of the globe. However, the first known landing is attributed to the Dutch sailor Willem de Vlaming in 1696. The two islands were visited by sealers and fishermen from the late eighteenth century onwards. Seal harvesting was intense and fur seals *Arctocephalus tropicalis* (Gray, 1872) were considered extinct in the late nineteenth century. After cessation of harvesting the population recovered and has stabilised (Guinet *et al.* 1994). The second half of the nineteenth century was marked by several scientific visits (*Novara* in 1857, Transit of Venus in 1874–75) and by an attempt at settlement on Île Amsterdam by Heurtin, a farmer from Île de la Réunion, in 1871. This attempt failed and Heurtin released five cattle *Bos taurus* Linnaeus, 1758 when leaving the island, one year later. The number of cattle quickly increased and was estimated at 1500 head in 1931 (Aubert de la Rüe 1932) and 2000 head in 1988 (Berteaux & Micol 1992). Cattle have been a significant cause of ecosystem disturbance, especially at low altitude, in conjunction with successive fires mainly caused by human activities.

A scientific and meteorological station, Martin-de-Viviès, was established in 1949–50 on the northeastern coast of Île Amsterdam at 30 m a.s.l. This station hosts about 40 people in summer and 25 people in winter.

Flora and fauna

The native flora includes *Sphagnum* species (note that *Sphagnum* peatlands do not occur on either Îles Kerguelen, or Archipel Crozet) and, on Île Amsterdam, one species of tree, *Phylica arborea* Thouars. In the late 1980s the *Phylica arborea* forest reported by early visitors had been reduced to small patches. Much of the native vegetation had disappeared and introduced plant species had become dominant (Frenot & Valleix 1990, Frenot *et al.* 2001).

The native invertebrate fauna includes endemic brachypterous or micropterous species, e.g., *Brachypteragrostis patricei* Viette, 1959 (Lepidoptera), *Trimicra pauliani*

Séguy, 1959 (Diptera), mainly present above 400 m a.s.l. Some introduced species, *Calliphora croceipalpis* Jaennicke, 1867 (Diptera), *Porcellio scaber* Latreille, 1804 (Isopoda), *Dendrodrilus rubidus tenuis* Eisen, 1874 (Oligochaeta) are widely distributed at all altitudes (Tréhen *et al.* 1990).

Habitat destruction and introduced mammals (brown rats *Rattus norvegicus* Berkenhout, 1769 and cats) have threatened the avifauna at Île Amsterdam. One-third of the original avifauna was endemic. Several species have now become extinct and only 10 species of birds actually breed on this island (Micol & Jouventin 1995), including the endangered Amsterdam Albatross *Diomedea amsterdamensis* Roux, Jouventin, Mougin, Stahl & Wiemerskirch, 1993 discovered in 1983 (Jouventin & Roux 1983). A restoration program was implemented in 1988 (Micol & Jouventin 1995): cattle were removed from the larger part of the island, a fence was erected to protect the peat bogs at altitude and the breeding area of the Amsterdam Albatross, and about 10 000 *Phylica* seedlings were planted between 1988 and 1993. At Île Saint-Paul, a small rock, La Quille, 100 m apart from the main island, is a sanctuary for several endemic bird species. Black rats and rabbits were eradicated from Île Saint-Paul in 1997 to allow these birds to re-colonise the main island. Mice are still present.

COMMERCIAL ACTIVITIES AT FRENCH SUB-ANTARCTIC ISLANDS AND SURROUNDING SEAS

Marine areas around Archipel Crozet and Îles Kerguelen are within the boundaries of the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR, 1982). Since 1994, exploitation of whales has been prohibited in the 200-mile Exclusive Economic Zone (EEZ) around the French sub-Antarctic islands, and commercial fishing here is strictly regulated. Measures include a ban on fishing in inshore waters, closed seasons and areas where appropriate, minimum size of fish, the need to hold a fishing licence, return of detailed catch records, and presence of observers at times.

Stock assessment and management are conducted with the expertise of Museum National d'Histoire Naturelle in Paris. The fight against illegal fishing is very active, including monitoring by satellite. The main targets of fisheries are the Patagonian toothfish *Dissostichus eleginoides* Smitt, 1898 and spiny lobsters *Jasus paulensis* Heller, 1862. Total allowable catches for the 2006–2007 season for Toothfish are 1100 tonnes at Archipel Crozet and 5000 tonnes at Îles Kerguelen in the EEZ, and for the lobster 390 tonnes at Île Amsterdam and Île Saint-Paul in territorial waters and in the EEZ.

Tourism in the French sub-Antarctic islands is strictly limited. Four times a year, eight to 16 tourists accompanied by a guide visit the islands briefly aboard the supply vessel *Marion-Dufresne*.

CONSERVATION AND MANAGEMENT

Several organisations are involved in activities in the French sub-Antarctic islands and interact for conservation and management issues. The Terres Australes et Antarctiques Françaises (TAAF), attached to the Ministry of Overseas Territories, is responsible for national sovereignty in the French sub-Antarctic islands. This overseas territory, created in 1955, is administered in Ile de La Réunion by a Préfet who is the representative of the French government. The Préfet is represented by a district head, replaced every year, at Alfred Faure, Port-aux-Français and Martin-de-Viviès stations.

The French Polar Institute (IPEV, Institut Polaire Français Paul Emile Victor), created in 1992, is the central agency for polar and sub-polar research. Several organisations are involved in this agency, namely: Ministry of Research, Ministry of Foreign Affairs, National Centre for Scientific Research (CNRS), French Research Institute for Exploitation of the Sea (IFREMER), French Atomic Energy Commission (CEA), Meteorological Agency (Météo-France), Space Agency (CNES), French Polar Expeditions (EPF) and TAAF.

The Committee for the Polar Environment (CEP), created in 1993, gives advice and recommendations on matters relating to environment and wildlife protection, protected areas, and management issues. The 11 members of this committee are appointed by several ministers: foreign affairs, environment, overseas territories, research and by the nature conservation council (Conseil National de la protection de la nature). Issues relevant to the environment can be referred to the CEP by these ministries, by the Préfet, or by the director of the French Polar Institute. Conservation and management in the French sub-Antarctic islands are regulated by successive laws and decrees. The 1938 National Park Act protected marine mammals (in particular fur seals and elephant seals) and some bird species. Specific access regulations became effective in 1985: access to some areas was reserved for scientific activities, and visits to several pristine or little-disturbed islands and areas were strictly restricted and had to be justified by compelling scientific aims. Since 2001, a TAAF committee has been in charge of surveys, inventories and conservation of historical and cultural sites.

Most of the previous regulations were reinforced in October 2006 when the islands were given the status of Nature Reserve (Réserve Naturelle nationale des Terres australes Françaises, decree n°2006-1211, 03/10/2006) which is the strongest protection available under French law. The Nature Reserve includes all terrestrial areas, internal and territorial waters of the three groups of islands, except for the territorial waters around Île de La Possession (Archipel Crozet) and several marine areas at Îles Kerguelen (fig. 2). The Préfet is in charge of the reserve management. The TAAF consultative committee is designated as the consultative committee for the Nature Reserve and the CEP is designated as the scientific committee to be consulted about the management plan and about every scientific issue relevant to environment. This management plan is being drawn up within a three-year period following the creation of the Natural Reserve on 3 October 2006. At present it is only possible to introduce the general regulations mentioned in the establishment decree. Regulations for terrestrial areas state:

- The importation of non-domestic animals to the reserve is prohibited.
- The importation of domestic animals is prohibited except for animals involved in public service or rescue tasks (this exception is likely related to shepherd dogs which are sometimes present at Îles Kerguelen where sheep farming occurs).
- It is forbidden to disturb, to damage, to export wild animals as well as their eggs, litter or nests, except for scientific or health purposes subject to authorisation.
- The importation of plants in any form is prohibited,

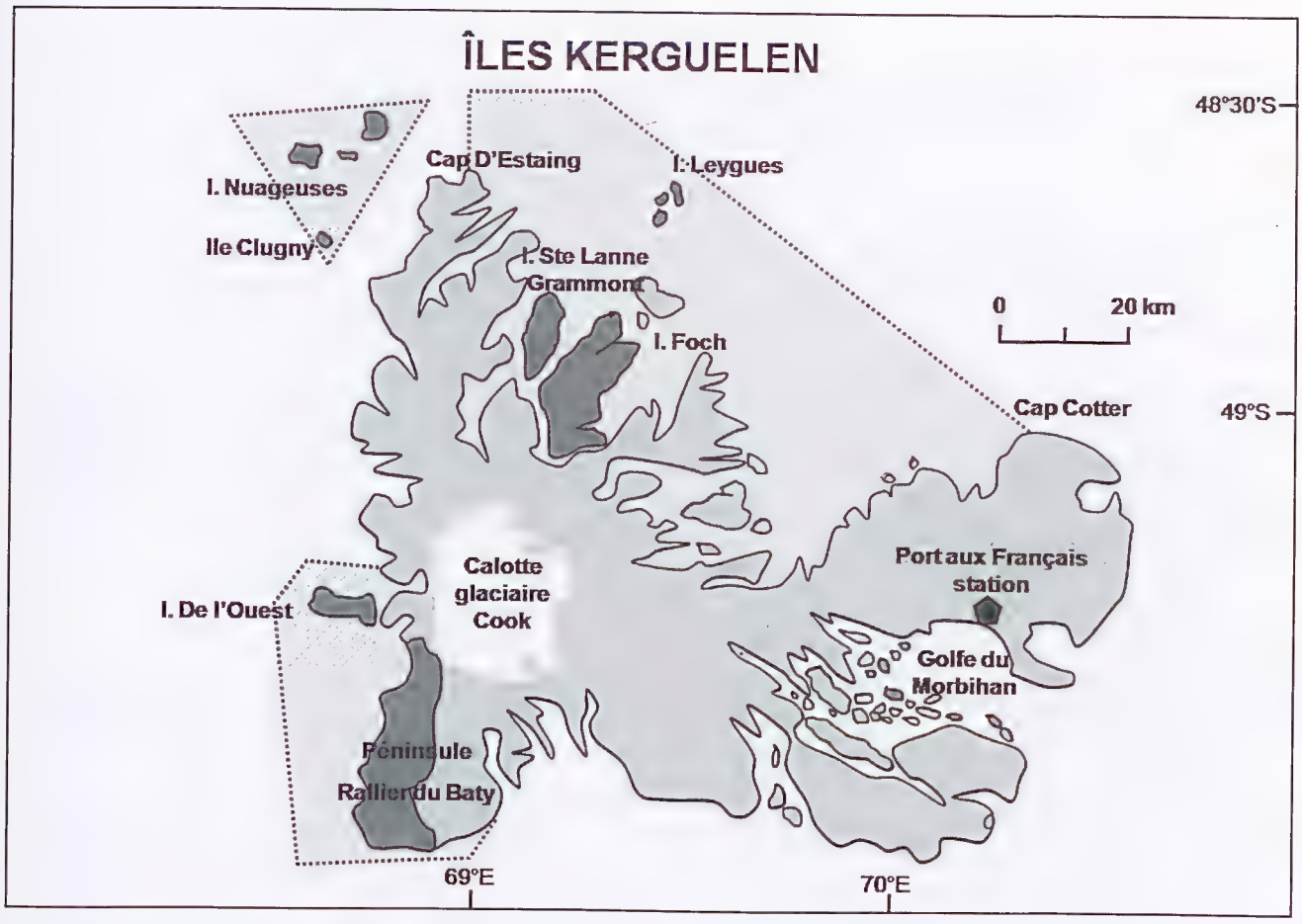

FIG. 2 — General map of Îles Kerguelen with the specially protected areas (dark grey) and the marine areas (hatched) included in the Nature Reserve.

except for the provision of the stations. (Greenhouse cultivation occurs at Crozet and Kerguelen islands, as well as outdoor gardening at Amsterdam Island).
- It is forbidden to damage wild plants, except for care tasks in the reserve, and to export them, except for authorised scientific, medical or paramedical purposes.
- Mineral prospecting and mining are prohibited.
- No geological samples may be collected or transported except for authorised scientific purposes.
- Various activities are regulated by the Préfet in accordance with the management plan of the Nature Reserve: control of alien species, waste management, fishing in fresh water, farming, tourism, sport, photography, filming.

Regulations for marine areas state:
- Fishing in the Nature Reserve is controlled by the Préfet.
- It is prohibited to destroy, to mutilate, to capture and to remove cetaceans.
- The location and use of anchorages are specified by the Préfet in accordance with the management plan.
- Apart from the authorised anchorages, vessels are allowed only to cross the marine areas included in the Nature Reserve.

Specially protected areas

The highest level of protection applies to some areas where any human activity is prohibited. Access to these areas is unauthorised except in the case of force majeure. However, dispensations may be granted.

The specially protected areas are the following: Îles Kerguelen (fig. 2): the west coast of Péninsule Rallier du Baty, IÎes Nuageuses, Îles Leygues, Île Cluny, Île de l'Ouest, Île Saint-Lanne-Grammont, Île Foch and several small islands in Golfe du Morbihan (Hoskyn, Pender, Bryer, Blackeney, Greak, Suhm, Antarès); Archipel Crozet: Île de l'Est, Île des Pingouins, Îlots des Apôtres, Île aux Cochons ; and Île Saint-Paul: the entire island.

It is anticipated that the new status of Nature Reserve will increase the overall protection of the terrestrial and marine environments and of the biotas of the French sub-Antarctic islands.

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MANAGEMENT FRAMEWORKS FOR THE NEW ZEALAND SUB-ANTARCTIC ISLANDS

by A. D. Roberts

Roberts, A.D. 2007 (23:xi): Management frameworks for the New Zealand sub-Antarctic islands. *Papers and Proceedings of the Royal Society of Tasmania* 141(1): 29–32. ISSN 0080-4703. Department of Conservation, PO Box 743, Invercargill, New Zealand. Email: aroberts@doc.govt.nz

The five island groups known as the New Zealand sub-Antarctic islands — Antipodes Islands, Auckland Islands, Bounty Islands, Campbell Island and Snares Islands — are perhaps better regarded as cool temperate although they share many features and many management issues with islands south of the Antarctic Convergence. The Snares and Bounty islands have granitic substrates; the Antipodes, Auckland and Campbell islands are of volcanic origin. Marine mammals and seabirds are important components of the fauna. Terrestrial flora and invertebrate fauna show high levels of endemism. Several species of alien vertebrates have been successfully eradicated. The islands are managed by the New Zealand Department of Conservation as National Nature Reserves, and together are recognised as a World Heritage Site.
Key Words: sub-Antarctic islands, cool temperate, Antipodes Islands, Auckland Islands, Bounty Islands, Campbell Island, Snares Islands, World Heritage Site, alien species removal.

The New Zealand sub-Antarctic islands are located south of New Zealand in the Pacific sector of the Southern Ocean. Although these islands are not truly sub-Antarctic but more correctly cool temperate, they share many features and many common management issues with islands south of the Antarctic Convergence. The New Zealand sub-Antarctic islands are mid-latitude islands lying between 47° and 53°S, between the subtropical convergence (which swings as far north as the Chatham Islands (44°S)) and the Antarctic Convergence (which sits around the latitude of Macquarie Island (54°S)). The islands are more heavily vegetated than most of the other Southern Ocean islands, but share elements of both the flora and fauna of the sub-Antarctic islands. They have faunas rich and diverse in albatross, penguins and marine mammals.

Circulation in the western Pacific sector of the Southern Ocean is influenced by the New Zealand continental shelf which forms a shallow platform interrupting the westerly flow of the Southern Ocean currents. Additional influences on circulation include the Solander Trench, the Macquarie Ridge and the action of the deep ocean currents that move along the southern edge of the Campbell and Bounty plateaux. The number of seamounts across the shelf indicates a history of volcanism near the edge of the Australian and Pacific plates (Kennedy & Hayward 1993).

SNARES ISLANDS

At 48°02'S, 166°35'E this small group is the most northerly of these islands, just 200 km southwest of the South Island of New Zealand. The group comprises ten islands, totalling 328 ha. The largest, North-East Island, covers 280 ha. The base rock is ancient granite set down about 100 MY BP (Kennedy & Hayward 1993). The mean temperature is about 11°C and annual precipitation is estimated at about 1200 mm.

There is a cover of woody vegetation of tree daisy *Olearia lyallii* Hook. and other components of shrub-type forest. The Snares Islands are the least modified island group in New Zealand, with no history of settlement, and no introduction of any pest species. There are several endemic bird species (penguin, snipe, passerines) on the Snares (Peat 2003).

There is evidence of Polynesian visitation in the pre-European period (Peat 2003). European discovery was in 1791.

AUCKLAND ISLANDS

The Auckland Islands form the largest group amongst the New Zealand sub-Antarctic islands. They are 460 km south of the South Island of New Zealand at 50°44'S; 166°05'E. There are more than 10 islands in the group totalling 62 560 ha, with the largest being Auckland Island at 50 990 ha. The islands are the remnants of two former volcanoes that were active around 10 MY BP (Kennedy & Hayward 1993). The mean annual temperature is around 11°C, with annual rainfall estimated at 1000–1500 mm.

There is a significant level of endemism in the indigenous flora and fauna. The island has elements of a Pacific biota: rata forest (*Meterosideros umbellata* Cav.), parakeets (*Cyanoramphus* spp.) and rails (*Rallus* spp.) as well as sub-Antarctic elements: megaherbs (*Pleurophyllum* spp. *Stilbocarpa* spp.), albatrosses (*Diomeda* spp.) and penguins (*Eudyptes* spp.).

There is also evidence of brief settlement by Polynesians around c.700 Y BP (Anderson 2006). European discovery occurred in 1806. The Auckland Islands have had some history of modifications through whaling, farming and the introduction of various pests (many of which have now been removed (Brown 2002, Torr 2002). Planning is under way for removal of feral pigs and cats.

CAMPBELL ISLAND

At 52°33'S, 169°10'E, Campbell Island is the southernmost of the New Zealand sub-Antarctic islands, being some 700 km south of New Zealand's South Island. The main island covers 11 330 ha and there are about six very small outliers. The island was volcanic, active about 6–11 MY BP (Kennedy & Hayward 1993). Mean annual temperature is 6°C, average annual precipitation is 1360 mm, and there is severe gale wind on at least 100 days annually.

The island has much in common with other sub-Antarctic islands, with some stunted shrubby vegetation, but is mostly covered in tussock (*Poa litorosa* Cheeseman) grassland. There is a number of endemic species including six albatross species — *Thalassarche impavida* Matthews, 1912, *T. chrysostoma* (Forster, 1785), *T melanophrys* (Temminck, 1828), *Diomedea epomophora* Richdale, 1952, *D. antipodensis* Robertson & Warham, 1992, *Phoebetria palpebrata* (Forster, 1785) — that breed on site (Peat 2003). The megaherbs (*Pleurophyllum* spp. *Stilbocarpa* spp., *Anisotome* spp. and *Bulbinella*) are spectacular.

European discovery was in 1810. The island has been farmed and burning had taken place although all animal pests (cattle, sheep, rats, cats) have now been removed (Brown 2002, McClelland & Tyree 2002).

ANTIPODES ISLANDS

The Antipodes Islands are the most distant from New Zealand being 850 km southeast of the South Island of New Zealand. They are located at 49°41'S; 178°45'E. The main island covers 2025 ha and together with several smaller islands and islets the area of the whole group is 2097 ha. The island was a former volcano last active less than 1 MY BP (Kennedy & Hayward 1993). Temperature is estimated at 8°C and the annual rainfall at 1000–1500 mm. Levels of endemism amongst flora and fauna are high (Peat 2003).

European discovery was in 1800. There has been little modification to the environment apart from the accidental introduction of mice (*Mus musculus* Linnaeus, 1758).

BOUNTY ISLANDS

The Bounty Islands are the most northern of the New Zealand Sub-Antarctic islands located at 47°45'S and 179°05'E. They are 700 km east-southeast of the South Island of New Zealand. The group comprises 20 very small islands totalling some 135 ha, remnants of granite outcrops that were laid down c.180 MY BP (Kennedy & Hayward 1993). Mean annual temperature is estimated at 10°C.

The islands are not vegetated and the fauna is dominated by albatross and penguins species (Peat 2003). European discovery was in 1788.

MANAGEMENT FRAMEWORKS

The framework for the sub-Antarctic islands administered by New Zealand is established via the New Zealand legislative system. The islands are administered by the Department of Conservation (DOC), the government agency responsible for the conservation of natural and historic heritage as well as providing for recreation on conservation lands. DOC administers 24 statutes and various regulations. Key statutes are: the Conservation Act 1987, National Parks Act 1970, Reserves Act 1977, Wildlife Act 1953 (all found at www.doc.govt.nz).

Each of the five island groups are National Nature Reserves under the Reserves Act. Nature Reserve status is the highest protective status possible under New Zealand law; the status "National" Nature Reserve means that the protective status can only be revoked by an Act of Parliament. The status of the New Zealand sub-Antarctic islands is consistent with most of the other islands around the southern ocean. The primary purpose of a nature reserve is protection and preservation of the natural features, species and environment. The Reserves Act also directs that the preservation of flora, fauna and ecological associations is accorded a higher level of value even than scientific interest or scientific research although science is still given high priority compared with recreational use. The boundary of the nature reserves is the spring tide mean low water mark. The five island nature reserves are together listed as a World Heritage Site (Peat *et al.* 1997) and under the International Union for the Conservation of Nature (IUCN) criteria, the islands would be regarded as strict nature reserves.

The Minister of Conservation (MOC) (as separate from the Department of Conservation) has a specific local government role under the Resource Management Act 1991. The MOC may place controls on any activity that might have an effect on the environment. The MOC has recently requested that the Department prepare a Regional Coastal Plan to cover marine activities within the tidal area and the territorial seas around each of the five islands.

The New Zealand government has a range of policy objectives for biodiversity protection and the objectives are agreed between four government agencies (Department of Conservation, Ministry of Environment, Ministry of Agriculture and Forestry, and Ministry of Fisheries).

The DOC has operational staff located in 50 management areas nationwide. The Southern Islands Area has staff based in both Invercargill (the southernmost city in New Zealand) and on Stewart Island (the southernmost populated island in New Zealand) and is responsible for the day-to-day management of the New Zealand sub-Antarctic islands. The Southern Islands Area covers Stewart Island (of which 92% is managed by DOC either as national park (85%) or other reserves) and a number of other nearby nature reserve islands and a marine reserve at Stewart Island as well as the five sub-Antarctic islands including a Marine Reserve and Marine Mammal Sanctuary at the Auckland Islands.

The Southern Islands Area has 26 full-time staff and a total annual operating budget (including salary, wages and operating) of NZ$2.4 million (2005) which covers management at both Stewart Island and the sub-Antarctic islands. No personnel are permanently based on any of the New Zealand sub-Antarctic islands. To visit the islands DOC staff use charter vessels (a 15-metre yacht and a 20-metre ex-fishing boat) and once every couple of years staff receive assistance from the Royal New Zealand Navy. In the 2006/07 summer there were six research expeditions, three management trips and three shorter research trips to the New Zealand sub-Antarctic.

CONSERVATION MANAGEMENT STRATEGY

Conservation Management Strategy Subantarctic Islands 1998–2008 (CMS) (Department of Conservation 1999) is the management planning document that guides the day-to-day management of the islands. The CMS was prepared for New Zealand's sub-Antarctic in 1998 and runs for a 10-year period. It is due to be reviewed in 2008. Four key management issues were identified during its preparation:

An island categorisation system was implemented and the system provided five different categories to assist island management by providing consistency (Atkinson 1990). It

is a nationally applied system but was particularly useful in the highly protected and high-value sub-Antarctic context. In the sub-Antarctic the two most protective categories — minimum impact and refuge — have been used. The Campbell Island setting illustrates this point: Dent Island (27 ha) has very important conservation value never having been modified by human influences, therefore it has been accorded minimum impact status. This status means that visits are tightly restricted, whereas Campbell Island (11 330 ha) as a refuge island is allowed a higher level of visitor use. In this context "visitor" means all persons visiting the island including management and research staff, rather than "visitor" just referring to tourists.

All visitor impacts are to be controlled on a precautionary basis. All visits to the islands pose some level of risk (such as pest incursion, oil spill, disturbance of wildlife breeding, etc.). Some of the more significant risks in terms of managing impact are visits by managers or researchers who might be undertaking pest control or significant scientific research, but there are also very considerable benefits from their visits. Therefore all visits are controlled through an entry permit system. *The Sub-Antarctic Island Research Strategy* (West 2005) identified priority research topics and is a means for assessing the benefits of research proposed for the sub-Antarctic. The *Research Strategy* was completed in 2003. The current research programme is mostly terrestrial in focus although there is an increasing focus on seabirds and marine mammals. Some marine research is being undertaken into describing the marine life with a focus on deep sea commercial fisheries research. There is also some work of more international significance in terms of plate tectonic investigations and climatological research.

The status of a potential plant pest species was clarified: the tree daisy species (*O. lyalli*) that was endemic to the Snares Islands 200 km south of New Zealand. It had arrived on the Auckland Islands within the past 200 years. Debate from botanists and island managers centred on whether it was a weed or not and whether it should be eradicated. The DOC used the CMS planning process to determine that the tree daisy could have got there via natural processes and there was no evidence that it had been directly introduced. The DOC has decided not to attempt to eradicate the tree daisy from the Auckland Islands and that its arrival should best be regarded as a naturally occurring colonisation event.

The CMS took a clear lead on the removal of pests from the islands and directed a pest eradication program. So far a range of pest species have been removed: cattle *Bos taurus* Linnaeus, 1758, rabbits *Oryctolagus cuniculus* Linnaeus, 1758, and mice *Mus musculus* from Enderby Island (710 ha); rabbits from Rose Island; goats *Capra hircus* Linnaeus, 1758 from Auckland Island (50 000 ha); as well as cattle, sheep *Ovis aries,* Linnaeus, 1758, cats *Felis catus* Linnaeus, 1758 and Norwegian rats *Rattus norvegicus* Berkenhout, 1769 from Campbell Island. The operation to eradicate Norwegian rats from the 11 330-ha Campbell Island required 120 tonnes of rodent bait, a team of 19 people, five helicopters which were flown from New Zealand, and six weeks of uncharacteristically good weather. The DOC has given the pest eradication work clear direction and priority, and a national advisory group of experts ensures that best practice and constant improvement occurs throughout the eradication programs nationwide (Cromarty *et al.* 2002). The only pests still to be removed are: mice from the Antipodes islands (2020 ha); and mice, cats and pigs *Sus scrofa* Linnaeus, 1758 from Auckland Island.

Other features of the management of the islands are links to threatened species recovery plans. Such activities include: monitoring of species populations; monitoring of species in conjunction with fisheries controls; and species reintroduction programs. There is a close focus on island biosecurity. An *Island Biosecurity Plan* (Agnew & Roberts 2004), which covers the DOC's island management operations across the southern portion of the South Island of New Zealand as well as the New Zealand sub-Antarctic islands is utilised and a stand-alone island quarantine store is established in Invercargill.

MANAGEMENT IN THE SURROUNDING SEAS

The management framework for the surrounding seas has the New Zealand Ministry of Fisheries responsible for fisheries quota management and in partnership with DOC for protected wildlife by-catch management and research issues. The DOC is responsible for marine reserves as well as marine mammal research and conservation issues, and the Ministry of Agriculture and Forestry (biosecurity section) is responsible for pest invasion matters, but at a national border level. Maritime New Zealand is responsible for marine pollution and oil spills within the 12-nautical-mile marine territorial limits.

The 12-mile territorial seas cover a large area around these islands, and by virtue of the far-flung nature of the islands establish quite a large 200-nautical-mile exclusive economic zone (EEZ). New Zealand's EEZ is 15 times its land area. There is a DOC-managed marine mammal sanctuary and marine reserve around the Auckland Islands extending out to the territorial waters. Currently marine protection for an area across the Campbell platform around the Campbell, Bounties and Antipodes islands is being investigated. The DOC expects a marine protection proposal to go to the Minister of Conservation and Minister of Fisheries for a sub-Antarctic Islands Marine Reserve by late 2008.

EXPECTATIONS FOR THE FUTURE

Removal of the last of the introduced animal pests is a priority, as is limitation of the impacts of human activities. Commercial fishing interactions with wildlife will continue, fishing pressure will continue as new species will be harvested. There will be exploration for gas and oil in the Great South Basin to the north and east of the islands. In all of that mixture these valuable sites will be managed for conservation purposes and along the way there is a considerable amount to be learned from each other as managers of remote oceanic islands.

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SOUTH GEORGIA AND THE SOUTH SANDWICH ISLANDS: THEIR CONSERVATION AND MANAGEMENT

by H. Hall

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South Georgia and the South Sandwich Islands are administered by the South Georgia and South Sandwich Islands Government, based in the Falkland Islands. Heavily glaciated South Georgia provides a land base for myriad seals and penguins. Responsible ship-based tourism is encouraged. The South Sandwich Islands, actively volcanic, consist of a 390-km-long chain of 11 main islands. Fisheries in the South Georgia Maritime Zone are managed using an ecosystem approach aiming to conserve the marine environment.
Key Words: sub-Antarctic, South Georgia, South Sandwich Islands, conservation, management, fisheries, tourism.

LOCATION AND PHYSICAL CHARACTERISTICS

South Georgia is a crescent-shaped island (~160 km long x 39 km wide). The backbone of the island is formed by two mountain ranges — the Allardyce and the Salvesen ranges. The highest peak is Mt Paget at 2934 m. It lies between 53°56' and 54°55'S but its position south of the Antarctic Convergence gives it a colder climate than other sub-Antarctic islands (Burton 2005). The South Sandwich Islands lie in an arc some 650 km further southeast. Most of the human activity in the region takes place in South Georgia.

South Georgia island is long and narrow. The north coast is relatively sheltered from the prevailing westerly winds and the fjords and bays along this coast provide protected anchorages. The south coast bears the brunt of the Antarctic storms (Stone & Walton 2002). Most human activity has therefore taken place on the north coast (Headland 1984).

Half of the island is covered with permanent ice and snow and numerous glaciers (Poncet & Crosbie 2005). There are about 20 major lakes and many smaller pools, mainly along the northwest coast. There are several satellite islands of which the main ones are Bird Island and the Willis Islands off to the west, Annenkov Island and the Pickersgill Islands off the southwest and Cooper Island to the east (Stone & Tanner 2004). In the far west, Shag Rocks are usually shrouded in mist (Stone & Smellie 2002).

The South Sandwich Islands are a 390-km-long chain of 11 main islands. They are actively volcanic and, despite being north of both the South Shetlands and South Orkneys, are significantly colder owing to the presence of the current from the Weddell Sea. The islands range in size from Leskov Island, which is less than 1.6 km long, to Montagu Island — 10 x 11 km — which is 90% permanently covered by ice. Mount Belinda on Montagu Island is still erupting and the island is gradually growing larger as a result (Patrick *et al.* 2005).

FLORA AND FAUNA

The terrestrial flora and fauna of South Georgia include 25 native species of higher plants and many lower plants. The dominant species is tussac grass, *Paradiochloa flabellata* (Lam.) Hook.f. There are 86 bird species found on the island — seabirds, coastal birds and land birds — of which 30 species breed, including four species of penguin, four species of albatross and numerous petrel species. Seals are the most numerous mammals, but there are also reindeer and rats which were introduced during the last century (McIntosh & Walton 2000, Burton 2005, Poncet & Crosbie 2005).

Marine fauna include principally krill, but there are also 41 species of fish and diverse benthic species (McIntosh & Walton 2000). Research into benthic species is ongoing, but there is still much to be done. Visiting whales feed in South Georgia waters.

From a wildlife point of view, the South Sandwich Islands are significant for being home to 1.5 million pairs of Chinstrap Penguins *Pygoscelis antartica* (J.R. Forster, 1781) (Burton 2005).

ADMINISTRATION

A representative of the islands' administration lives on South Georgia at King Edward Point but the majority of administration is carried out from outside the islands by a small team of four people, who contract in outside expertise as necessary. The official address of the Government of South Georgia and South Sandwich Islands is Government House, Stanley, Falkland Islands, South Atlantic. Two scientific bases permanently staffed and managed by the British Antarctic Survey engage in a variety of scientific research topics, including applied fisheries research and ecosystem monitoring. There are also shorter-term projects by visiting scientists.

South Georgia is financially self-sufficient, although the British Antarctic Survey Research stations are part-funded by the Government of the United Kingdom. The vast majority of revenue for the island comes from the sale of fishing licences which totals roughly £3.5 million a year. The second largest revenue source is landing fees from tourists and other visitors but this is still less than £0.5 million. The single largest expense is fisheries management and includes both research and protection. Over the past five years revenue and recurrent expenditure has risen fairly constantly. Major public works projects have incurred significant capital expenditure which has drawn on the islands' reserves.

CONSERVATION AND MANAGEMENT

The first Environmental Management Plan was published in 2000 and set out background information and management

policies for the island of South Georgia. According to the commitment in that plan, a review was carried out in 2006 and, following extensive consultation with stakeholders, an update to the plan was published in August 2006 (Pasteur & Walton 2006).

The key policy aims which govern the management of the island are:

- To conserve the native flora and fauna and natural environment of South Georgia. To prevent further introduction of alien flora and fauna and to eradicate or control previously introduced species that affect or endanger native species or habitats.

  Preliminary work is underway to examine the feasibility of eradicating rodents on South Georgia. Consideration is being given to culling one of the two herds of reindeer with a view to studying the impact of removing this species. It is also vital to prevent further introductions of alien species and stricter controls on all visitors and the import of all equipment are being introduced.
- To record and conserve the historical heritage of South Georgia, including significant examples, for future generations.

  Previous human activity on South Georgia, although often regrettable, is an unavoidable part of the island's history. As well as being a reminder of the horror of the whaling and sealing industries, the island's historic heritage is a demonstration of human ingenuity and endeavour. The Lutheran church at Grytviken is now a major attraction for visitors and Christmas carol services in particular are still held annually. The grave of Sir Ernest Shackleton is also a place of pilgrimage for many.
- To encourage sustainable tourism and use revenue generated to improve the environmental management of the islands.

  Conserving South Georgia's unique natural and historic heritage does not mean isolating the island. Although not officially a World Heritage Site, South Georgia is a unique place which many regard as a global asset. Allowing visitors to see this for themselves is an important way of raising awareness and educating people about the "specialness" of the place and the challenges faced by its natural inhabitants. To do this with minimal impact, careful monitoring of visitor numbers occurs and all visitors must follow guidelines on behaviour. Cruise-ship tourism, under the umbrella of the International Association of Antarctic Tour Operators (IAATO), remains the principal way of visiting the island. There is no air access, nor is there likely to be any.
- To manage human activities so that they cause minimal adverse impacts on the fauna, flora and natural features of South Georgia and to encourage activities aimed at restoring and rehabilitating damage caused by previous human activities.

  Plans for activities on South Georgia should be accompanied by an Initial Environmental Evaluation (IEE) or Environmental Impact Assessment (EIA), depending on the scale of the activity. Large-scale restoration projects, such as the recent clean-up of the former whaling station at Grytviken, may be undertaken when funds are available. There are also plans to restore the former dam at Grytviken and install a hydro-electric power plant, to make human activities on South Georgia mainland carbon-neutral.
- To manage sustainable fisheries in the South Georgia Maritime Zone (see map in McIntosh & Walton 2000) using an ecosystem approach and to conserve the marine environment.

  The fisheries around South Georgia are managed in accordance with the precepts and conservation measures of the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR). The recent award of Marine Stewardship Council certification for the toothfish fishery on South Georgia. has led to higher standards of operations in these waters and has also helped raise consumer awareness of sustainable and environmentally-conscious fishing practices. Although the spotlight tends to be on the toothfish fishery because this is the most valuable, research and development into other commercial fisheries, in particular for icefish and krill, continues (Agnew 2004).
- To encourage high-quality research to enhance the understanding of South Georgia's history and natural environment and contribute to regional and global conservation.

  Limited funds means that not all desirable research can be undertaken. The highest priority is given to fisheries research which underpins the economy and to research which is directed towards filling international commitments, such as those made under the Agreement for the Conservation of Albatross and Petrels.

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ORIGIN AND EVOLUTION OF THE SUB-ANTARCTIC ISLANDS: THE FOUNDATION

by Patrick G. Quilty

(with 23 text-figures and two tables)

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Sub-Antarctic islands have a diversity of origins in detail but most are volcanic and very young suggesting that they are short-lived and that the distribution would have been very different a few million years ago. They contrast with the common tourist brochure concept of oceanic islands. As the Antarctic Plate is virtually static, the islands seldom show signs of association with long-lived linear island chains and most thus stand alone. Longer-lived islands are either on submarine plateaux or are continental remnants of the dispersion of Gondwana. The islands are classified in relation to raised sea-floor, transform fault, triple junction, subduction zone, submarine plateau, submerged continent or continental. Many are difficult of access and poorly known geologically. Their geological history controls their many other roles such as sites as observatories, or for study of colonisation, evolution and speciation rates.

Key Words: Sub-Antarctic islands, geological evolution, Macquarie Island, Balleny Islands, Scott Island, Campbell Island, Antipodes Island, Auckland Islands, Enderby Island, Peter I Island, Islas Diego Ramirez, South Georgia, South Sandwich Islands, Bouvetøya, Gough Island, Marion Island, Prince Edward Island, Îles Crozet, Amsterdam Island, St Paul Island, Kerguelen Plateau, Îles Kerguelen, Heard Island, McDonald Island.

INTRODUCTION

The sub-Antarctic for this paper is taken as the area of the sea-floor and land between the base of the Antarctic continental slope and a poorly-defined latitude, normally somewhere about 50°S but also extending well north of that to include Gough Island at 40°21'S and Amsterdam and Saint Paul islands at 35–38°. It includes the islands of interest to the Scientific Committee on Antarctic Research (SCAR) (Bonner & Lewis Smith 1985, Dingwall 1995). One criterion for inclusion is the absence of a permanent resident human population. It thus includes the greater part of what is now termed the Antarctic Tectonic Plate (fig. 1), a few pieces of the African, Australia-Indian and Pacific tectonic plates, and a series of tectonic micro-plates north of the Antarctic Peninsula. The sea-floor of the area formed as part of the break-up of the super-continent of Gondwana, beginning some 160 million years ago — mid-Jurassic in geological terms (fig. 2) and representing events in the last 3.5% of Earth history.

Knowledge of the origin and evolution of the islands is critical to any consideration of the time constraints on other features of the islands such as landform evolution or biological diversity.

The total area of the sub-Antarctic islands is <14 000 km² (table 1) but if the largest island groups (South Georgia and

TABLE 1
Sub-Antarctic islands considered in this review, showing location and area

Island	Location	Area (km²)	Age (Ma)
Amsterdam & St Paul	35°52'–38°43', 77°30'E	58	< 0.5
Antipodes Island	49°41'S, 178°46'E	20	< 0.5
Auckland Island	50°50'S, 166°05'E	620	Continental
Balleny Islands	66°55'S, 163°20'E	400	< 10
Bouvetøya	54°26'S, 3°25'E	50	< 1
Campbell Island	52°33'S, 169°09'E	120	Continental
Îles Crozet (Possession)	46°25'S, 51°38'E	400	9–0
Diego Ramirez	56°30'S, 68°42'W	c. 2	Continental
Gough Island	40°21'S, 9°55'W	65	1
Heard & McDonald Is.	53°06'S, 73°31'E (Big Ben)	380	40, 9, 1–0: Active
Îles Kerguelen	49°21'S, 70°12'E	6500	39–25; 23–17
Macquarie Island	54°30'S, 158°57'E	200	9
Marion & Pr. Edward Is.	46°52'S, 37°51'E (Marion)	350	0.45–Recent
Peter I Island	68°50'S, 90°35'W	c. 200	0.3–0.1
Scott Island	67°24'S, 179°55'W	<1	"very young"
South Georgia	54°17'S, 36°30'W	3755	Continental
South Sandwich Is.	56°20'–59°20'S, 26°–28°W	618	3, 1: Active

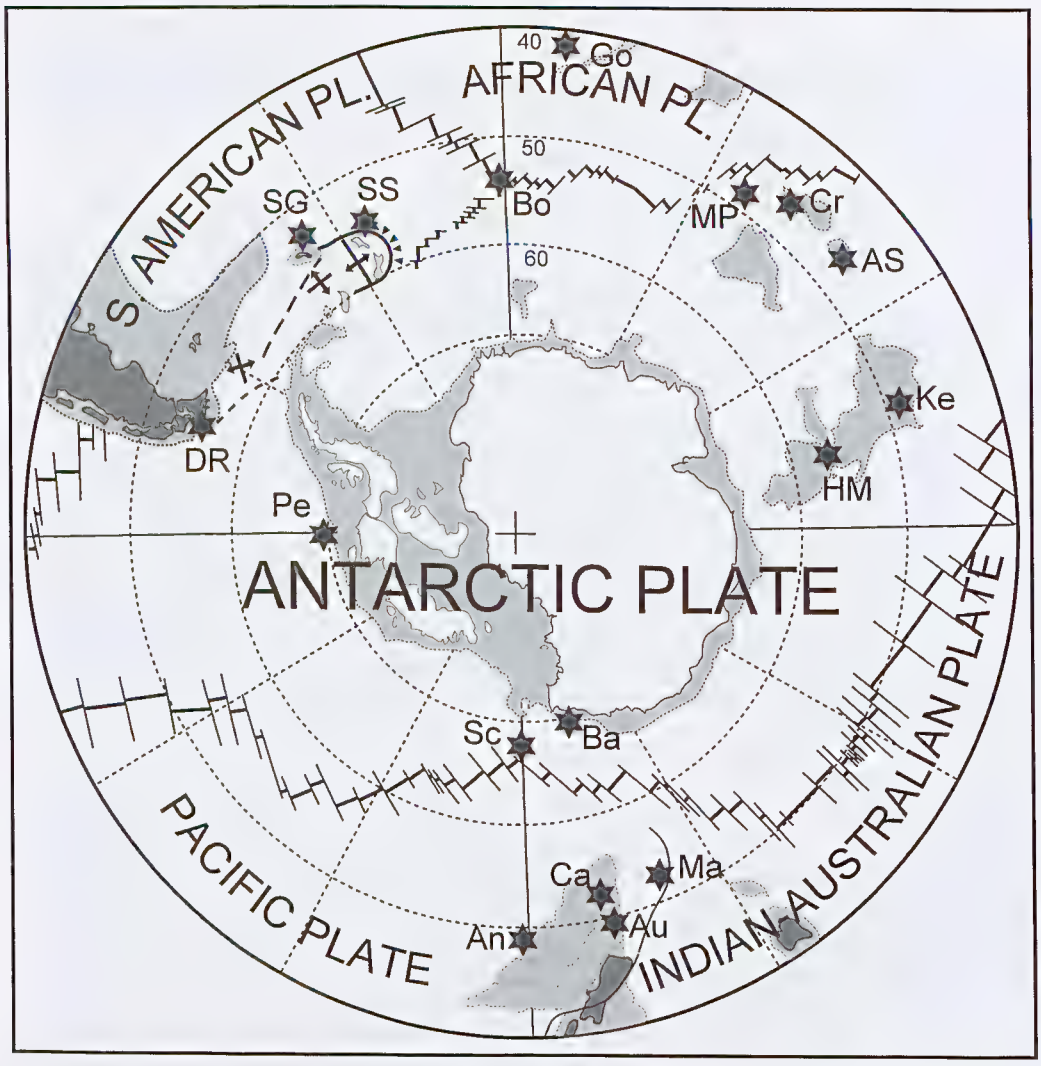


FIG. 1 — Islands of the sub-Antarctic in their plate tectonic context. AS = Amsterdam & St Paul Is.: An = Antipodes Is.; Au = Auckland Is.; Ba = Balleny Is.; Bo = Bouvet Is.; Ca = Campbell Is.; Cr = Crozet Is.; DR = Diego Ramirez Is.; Go = Gough Is.; HM = Heard & McDonald Is.; Ke = Kerguelen Is.; Ma = Macquarie Is.; MP = Marion & Prince Edward Is.; Pe = Peter I Is.; Sc = Scott Is.; SG = South Georgia; SS = South Sandwich Is.

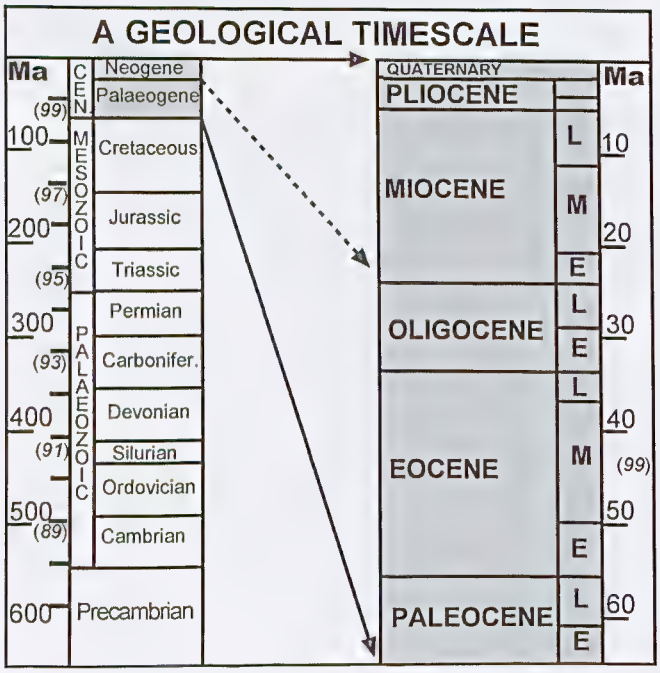


FIG. 2 — Geological timescale employed. This covers the last 600 million years. Numbers in italics and parentheses are percentages of Earth history that has passed before this time.

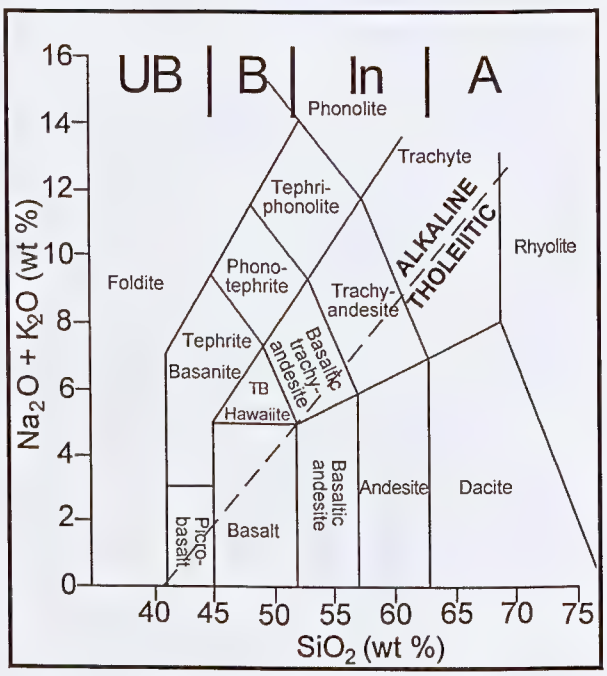


FIG. 3 — Classification of volcanic rocks including most of the types referred to in this paper. TB = trachybasalt: UB = ultrabasic (or ultramafic): B = basic (or mafic): In = intermediate: A = acid.

Îles Kerguelen) are excluded, the figure is slightly over 3000 km². For all their being small specks in a vast area, they are valuable as sites for marine-based organisms to inhabit, breed and moult, and for humans to build observatories. Their history provides controls on rates of evolution and colonisation. In recent years, many international programs (such as the Deep Sea Drilling Project and Ocean Drilling Program) have been concerned with the evolution of the oceans and ocean floors which cover 71% of the earth's surface. The sub-Antarctic islands, largely volcanic (using that term broadly), are relatively accessible sites allowing access to a variety of volcanic rocks and assist in gaining an understanding of the sources of oceanic lavas and conditions at the sites of generation of these lavas in the earth's mantle.

The islands are often on structures such as Macquarie Ridge and Kerguelen Plateau that have very great significance oceanographically by controlling the direction of deep water flow and in many instances, the shallow water flow, especially as that varies during periods of low sea level — for example at glacial maxima. Some of these major structures have varied in depth for tectonic reasons over time and such variation, coupled with changing continental positions, has had an influence in the longer term evolution of global climate.

Concepts of islands are commonly influenced by brochures and images of the Indo-Pacific where clean white carbonate reefs and atolls abound and where Darwin developed the concept of atolls forming as rings around the top of progressively submerging volcanoes. Such island chains are attributed to migration of tectonic plates over a "melting anomaly" or "hot-spot" within the mantle. Islands in the Pacific Ocean commonly, almost normally, are in the form of linear chains such as the Hawaiian island chain, with an active volcano at one end of a sequence of islands that are getting older, lower and more highly eroded with time and distance from the modern volcano. Individual islands form during a single episode of volcanism over perhaps a million years, when activity ceases for a while as the oceanic crust moves over the hot-spot — the source of the lava from various depths in the earth's mantle. After a few million years, eruption begins again but by this time the chain has moved and a new volcano and island forms. Eventually the islands subside below sea level to become a *seamount*, or, if flat-topped, a *guyot*. In most oceans of the world, hot-spot sites are used to measure movement of the tectonic plate over such hot-spots but the Antarctic plate is different in that it is essentially stationary and thus provides a good site for studying aspects of the hot-spots themselves. Hot-spot linear island chains are not to be expected. The distribution and features of sub-Antarctic islands lead to questions of the too-ready acceptance of the "hot-spot/plume" concept as an explanation for all phenomena.

The Earth has two surface expressions. Continental crust floats above the earth's mantle and thus has the potential to retain its entire 4.5 billion-year-history, in contrast with oceanic crust which is regularly subduced into the mantle and thus modern oceanic floors have a maximum age of about 180 million years. As continents move apart, new sea-floor is generated at a *mid-ocean ridge* (MOR) such as that between Australia and Antarctica, or roughly centrally in the Atlantic Ocean. The elevation of the ridge is normally at about 2.8 km water depth and this is the depth at which basaltic sea-floor generally forms. Segments of ridge crest are offset by *transform faults* which have a characteristic geometry. Ridge crests are the site of smaller, shallow earthquakes in contrast to subduction zones where large, deep, catastrophic earthquakes are more prevalent. Ridge crests, are the site of the phenomena associated with "black smokers" and their unusual life forms commonly attracting widespread interest because of their ability to live under extreme physico-chemical conditions.

This paper follows a route (fig. 1) from Tasmania, through Macquarie Island, Balleny islands, via Scott Island to the New Zealand sub-Antarctic islands on Campbell Plateau, then east to the Antarctic Peninsula/South American region and South Atlantic Ocean, before entering the Indian Ocean and terminating at the Heard and McDonald islands.

The aim is to summarise at a consistent technical level, the geological evolution of the islands as a basis on which other sciences can build, for example by showing how old the islands are and the influence age has on colonisation and subsequent rates of evolution. It also attempts to classify the islands according to origin and draw out the difference between sub-Antarctic islands and the popular conception of more temperate and tropical islands. While most research on the sub-Antarctic has concentrated on the volcanic rocks, several areas have substantial sedimentary sequences of a variety of ages and sedimentary environments, including Quaternary peat or glacial deposits. The comments in this paper refer mainly to the geology of the islands themselves and not so much to the geology of the surrounding sea-floor, other than to a general summary of the evolution of that sea-floor.

The reference list is not comprehensive and lists only enough papers to provide an adequate summary of the geology of the individual islands. Brief summaries of the volcanic characteristics of many are provided by a variety of authors in LeMasurier & Thomson (1990) who consider only those islands that are specifically volcanic and include many that are not considered here: conversely, this paper includes several not covered by LeMasurier & Thomson (1990).

The following terminology is used in this paper. Ma is used to denote the age in millions of years before present; ka refers to thousands of years; m.y. is used to indicate an age difference, whenever that may have been. Figure 2 is a geological timescale employing that used by Geoscience Australia, modified in the younger section by reference to Berggren *et al.* (1995).

Most of the rocks encountered on the sub-Antarctic islands are volcanic in origin. One classification of such rocks, based on SiO_2 and Na_2O and K_2O content, is shown in figure 3.

The break-up of Gondwana has had a critical influence on the region. When Gondwana began to disintegrate (160 Ma), Antarctica had been situated roughly over the South Pole for approximately 150 million years since moving south from the Northern Hemisphere. The region over the South Pole was all continental crust with distant ocean surrounding it. None of the sea-floor evident around Antarctica today existed. The entire super-continent at 160 Ma was populated with plants and dependent animals with much in common throughout the various modern fragments of Gondwana. Convenient summaries of the evolution of Gondwana are contained in Cande & Stock (2004 – Australia-New Zealand-Antarctica), Larter *et al.* (2002 – Pacific sector), Cunningham *et al.* (2002 Pacific sector), Royer & Sandwell (1989 – Indian Ocean), and Royer & Coffin (1992 – Indian Ocean).

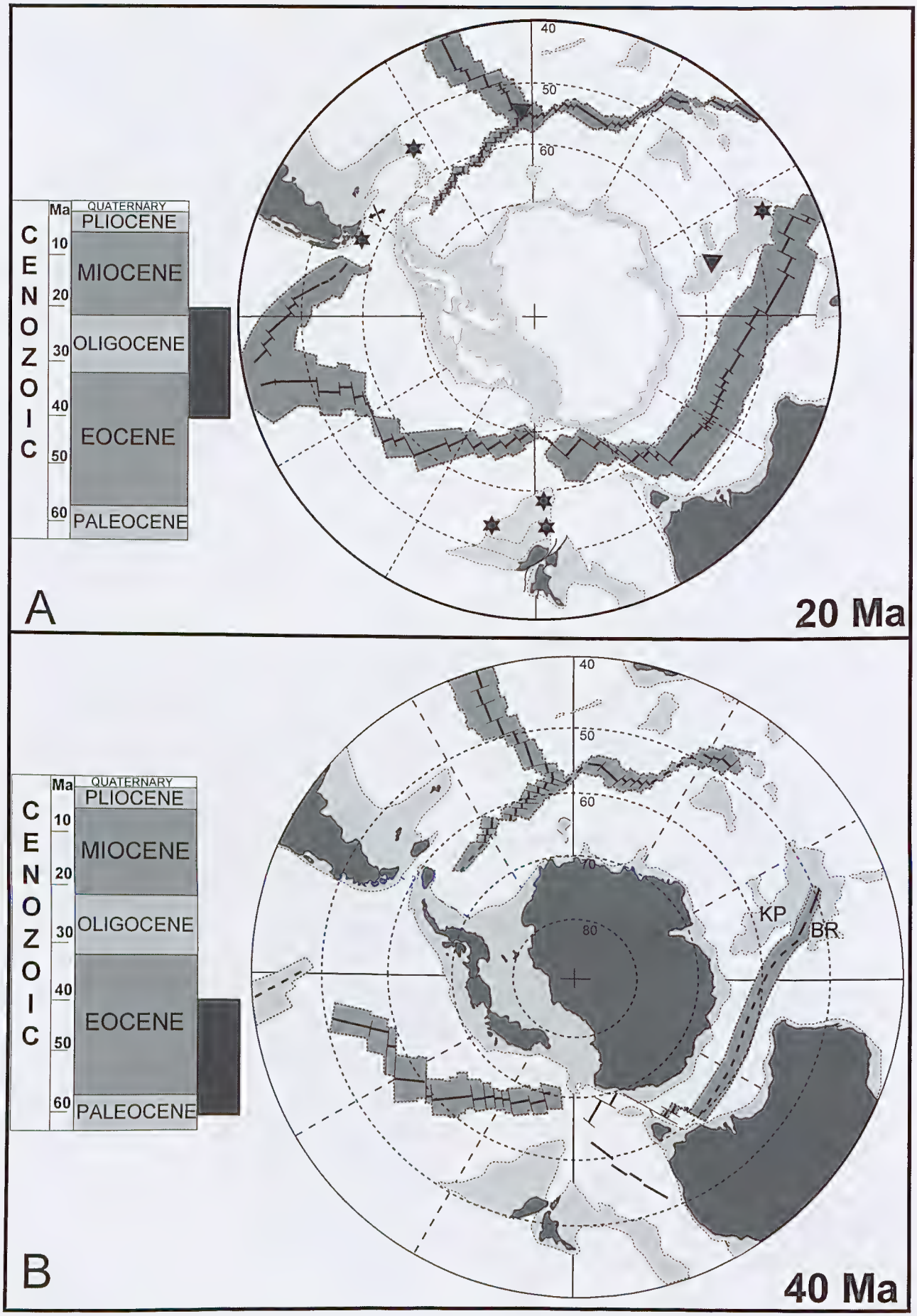


FIG. 4 — Antarctic Tectonic Plate boundaries at (A) 20 Ma and (B) 40 Ma. The area that grew at mid-ocean ridge in the previous 20 m.y. is shaded. Stars represent islands that existed at the time (see also fig. 1); triangles, islands that existed in part. Antarctica shaded in 4B to indicate that it was vegetated in contrast to 4A when it is white to indicate a glaciated state.

Figure 4 illustrates the evolution of the Antarctic Plate between 40 and 20 Ma and each of the two maps shows the amount of sea-floor formed (and thus dispersion of the continents) in the previous 20 m.y.

At about 55 m.y., Australia accelerated its movement north to its current rate of about 6 cm/year. This was to have momentous consequences. By 34 Ma (Exon *et al.* 2004), Australia had moved north far enough that deep-ocean circulation could occur between Australia and Antarctica. With the development of deep ocean circumpolar circulation, Antarctica was completely isolated (as were Australia and South America) and assumed its current glaciated state with the consequent extinction of almost all terrestrial fauna and flora. It developed an icesheet and 99.3% of Earth history had passed by this time. The Southern Ocean linked the Indian, Pacific and Atlantic oceans and washed Antarctica's shores. The oceanic crust of the Southern Ocean continued expanding by growth at mid-ocean ridges, but hardly any of the sub-Antarctic islands had come in to being by 20–30 Ma.

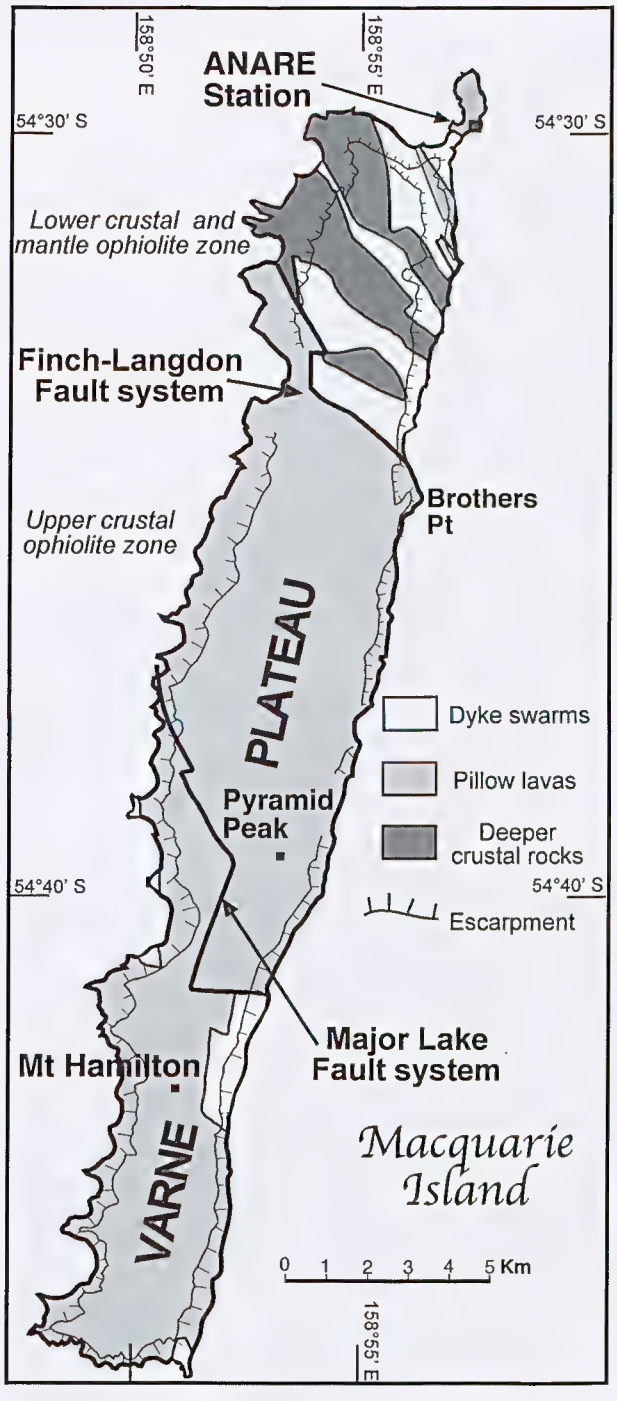


FIG. 5 — Macquarie Island

MACQUARIE ISLAND

Macquarie Island (Banks & Smith 1988, Selkirk *et al.* 1990) is on the Pacific Plate, very close to and east of the boundary between the Australian/Indian and Pacific Plates (fig. 1). Macquarie Ridge, first identified by Bellingshausen in1820, marks that boundary which is tectonically very active at present and large earthquakes are common. Macquarie Ridge links Macquarie Island and New Zealand where it continues as the Alpine Fault. The island (fig. 5) is marked by a surface plateau, the main part now identified as Varne Plateau, falling from over 400 m at its southern end, to about 250 m at the north. This probably represents old sea floor and some small hills may be remnants of submarine volcanoes. The plateau is surrounded by steep scree slopes on which landslips are common. The rugged western side of the island is separated from the ocean by a narrow raised platform; this feature is less well developed on the eastern side but where present, provides a convenient site for penguin and seal colonies. The surface of the island has been disrupted by faulting and small scarps are obvious and common.

The rocks that make up Macquarie Island (Varne *et al.* 2000) formed at a mid-ocean ridge at 9 Ma (Late Miocene; Quilty *et al.* in press). Dating rocks has been difficult but recent discovery of enigmatic bolboforms has provided a precise fossil-based date on the assumption that extrusion of pillow lavas and deposition of sediments was coeval. The island is cut by two complex transform faults — the Finch-Langdon and Major Lake Fault systems (Wertz *et al.* 2003). It consists of a variety of igneous and sedimentary rocks typical of a cross section through the oceanic crust (Varne *et al.* 1969). North of the Finch-Langdon Fault System, the rocks are from deeper in the crust and include a greater variety of intrusive rocks (gabbro, peridotite, dolerite dyke swarms and extrusive volcanic basalts, in addition to sediments including deep-sea nanno/foram ooze and volcanic sediment). In contrast, those of the southern 80% of the island are more like the near-surface rocks of the ocean floor with a higher concentration of pillow lavas and sediments. The complex formed initially at a slow spreading mid-ocean ridge/transform fault complex, probably at an ocean depth of some 2.8 km. With time, it sank into deeper water but probably not below the carbonate compensation depth (CCD) as carbonate sediments commonly show no evidence of dissolution.

Interaction between the tectonic plates led to uplift of the island and that process continues. Macquarie Island contains many old beach levels attesting to past coastlines. It is unclear what the current rate of uplift of the island is and it may vary from place to place. Adamson *et al.* (1996) reviewed various possibilities and suggested that Macquarie Island emerged above sea level approximately 600 000–700 000 years ago. Since the first emergence, the amount of the island above sea level has varied greatly, reflecting both tectonic instability and changes in global sea level consequent on climate changes.

The unique geological features of the island as a well-preserved cross-section through oceanic crust were the basis for its inscription, in 1997, on the World Heritage List.

BALLENY ISLANDS AND SCOTT ISLAND

The five major Balleny islands (fig. 6) form a linear series related to the Tasman Fracture Zone, a zone of closely spaced transform faults that passes from Antarctica, via the Balleny islands, to the southern and western margins of Tasmania. Because of their steep coasts, access to the islands is difficult and much work remains to be done. The islands are the subaerial expression of a series of submarine ridges including the Balleny Seamounts to the northwest, the ANARE Seamounts to the southeast, and farther southeast and parallel is another seamount chain — the Admiralty Seamounts. The entire complex lies very close to the location of a transform fault (Lanyon 1994) but the relationship with that fault is not clear. The Balleny island chain with its submarine extensions is oriented north-northwest–south-southeast parallel to the local transform faults.

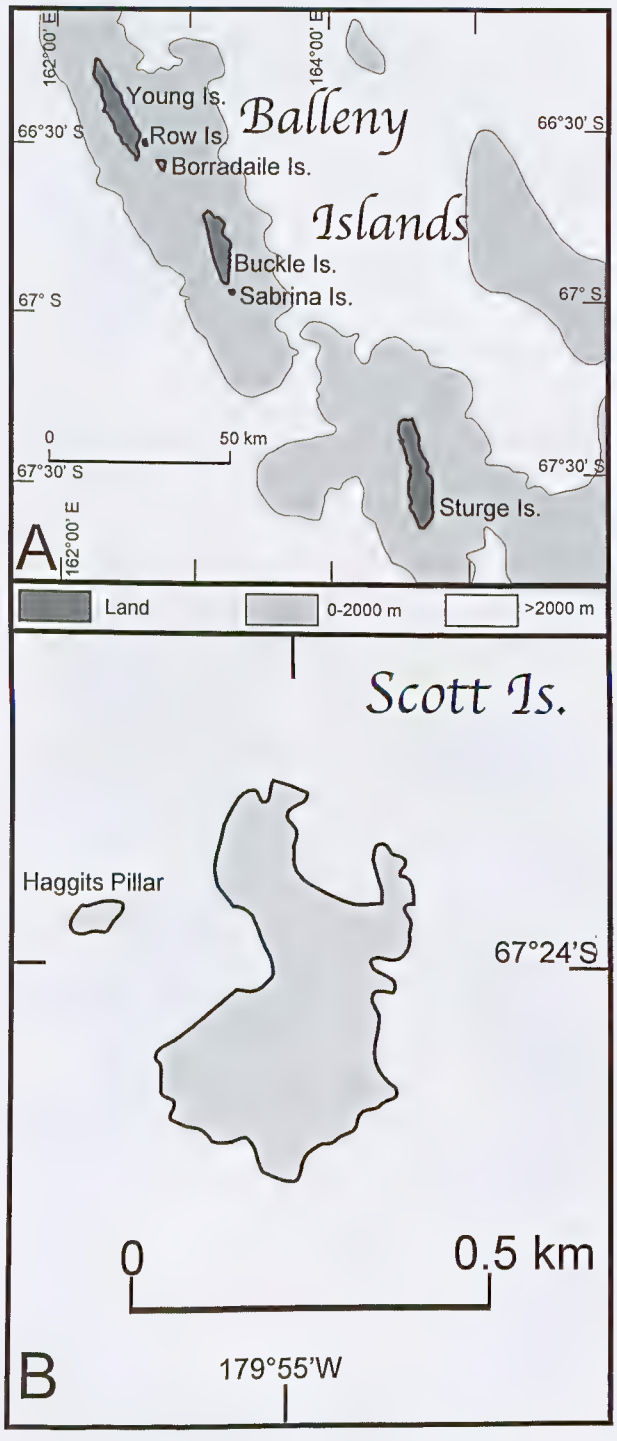


FIG. 6 — (A) Balleny islands and (B) Scott Island.

The islands formed by subaerial volcanic activity and the rocks are olivine trachybasalt with minor olivine-augite basalt and fit in the basanite–hawaiite field (fig. 3). They are in the form of agglomerates, tuffs and lava flows with obvious stratification, sporadically red-coloured due to oxidation at the time of eruption. The Balleny island chain has been linked to the evolution of New Zealand but a fracture zone/transform fault link with southern or western Tasmania is more accurate. These islands have been attributed to hot-spot activity (Green 1992, Lanyon *et al.* 1993, Lanyon 1994) but it has also been suggested that they result from intermittent activity along a transform fault that is under some oblique tension and thus could be "leaky" (Kyle & Cole 1974), and in this regard may be similar in origin to Gough Island. The islands are close to the site of a major earthquake in March 1998, the largest magnitude earthquake recorded in that year to that time.

The age of the volcanism is not well documented but analysis of nearby sea-floor magnetic lineations suggests that they are all less that 10 Ma. Radiometric dating of samples from the southern island — Sturge Island — indicates a Quaternary age of less than 2 Ma (Embleton 1984, Jenkins *et al.* 1992). Reports of many early expeditions stated that the islands were in eruption but there is no evidence that this is true and no modern infrared satellite imagery has detected any evidence of heat sources; the confusion probably stems from the unusual cloud formations that appear normally to cover the islands.

Tiny Scott Island seems to be a relatively normal volcanic island but it is not well studied. Its age is not known but is believed to be very young. It is the small projection above sea level at the northern end of a small, north-south oriented plateau (Scott Plateau — 145 x 30 km) which in turn sits on Eocene (about 40 Ma) sea-floor. Part of the Plateau is northwest-southeast oriented and is parallel to the Scott Seamount chain about 65 km to the southwest. This chain in turn is parallel to the Balleny Seamount chain and the histories of the two island groups are connected. Wright & Kyle (1990b) summarised what was known at the time and Lanyon (1994) examined further samples collected by dredging from adjacent to Scott Island.

The rocks of the island and surrounds are described as phonolites and phonotephrites, characterised by high Na_2O+K_2O (normally 12–13% in the phonolites and 9% in the phonotephrites) and thus are very similar to the Balleny Island rocks and have a similar origin.

CAMPBELL PLATEAU ISLANDS

South of New Zealand is an extension of thinned continental crust about 25 km thick in contrast to the usual 40–50 km and thus it lies below sea level. The area is the Campbell Plateau and an eastern extension — the Bounty Platform — and is host to several islands or island groups — Campbell, Auckland and Antipodes islands — all lying north of the Antarctic Polar Frontal Zone. The islands contrast markedly with most sub-Antarctic islands geologically and historically. The basement of Campbell Plateau (Beggs *et al.* 1990) includes mica-rich granite with ages in the range of 92–115 Ma, similar to those which make up the Snares islands some

450 km due north of Auckland islands and also on Campbell Plateau. The granite intruded into older metasedimentary rocks (micaceous quartzite) similar to that known from Antarctica, New Zealand and the South Tasman Rise and thus is similar in setting and age to others well known from the former Gondwana.

Antipodes Island is somewhat unusual among this group in being entirely volcanic in its exposed geology. The other island groups — Campbell and Auckland — have a basement of continental rocks with a longer geological history, the continental crust acting as foundation for major shield volcanoes — similar to those of the eastern coastal region of South Island, New Zealand, i.e., near Christchurch and Dunedin — with low angle slopes, circular outline and a gentle form of eruption of low viscosity basaltic lava. The shield volcanoes at Campbell and Auckland islands were about the same size, around 25 km in diameter.

Antipodes Island

Although Antipodes Island (fig. 7) sits on the thinned continental crust of Campbell Plateau, the basement does not outcrop and what is preserved is the product of volcanic activity during the Pliocene and Quaternary (1–5 Ma) (Peat 2003) but Gamble & Adams (1990a) suggest that the ages are generally younger, less than 1 Ma, probably < 0.5 Ma.

Antipodes Island is much smaller than either Campbell or Auckland islands and has two peaks — mts Galloway and Waterhouse — marking the position of the central volcanic cone and many smaller remnants. The highest point is 366 m but most of the island is an undulating plateau with cliffed margins to 150 m which show that much of the island consists of columnar basalt, the result of gentle eruption of low viscosity lava. The main lavas are low silica porphyritic lavas (basanite) with phenocrysts of olivine

To the northeast of the main island are two smaller islands (Bollons and Archway) which between them mark the eroded remains of a small volcano.

Antipodes Island shows no signs of having been affected by glaciation but has suffered considerable alluvial erosion to generate deep gullies. Like other Campbell Plateau islands, Antipodes Island has a layer of peat to 5 m thick.

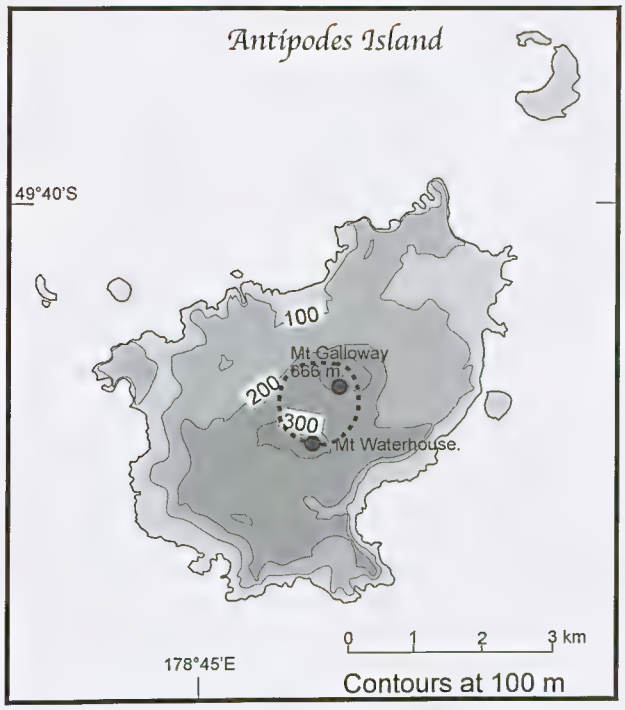


FIG. 7 — Antipodes Island

Campbell Island

Campbell Island (fig. 8) consists of the remnants of one shield volcano but its western side has been eroded away leaving only the eastern part. The centre of the volcano is thought to have been at about Dent Island. Older sedimentary rocks are exposed around Northwest Bay, and the entrance to Perseverance Harbour.

The sediments around the margins of the southwestern part of the island (Northwest Bay, Penguin Bay, Rocky Bay and Tucker Cove in Perseverance Harbour) include a section of Cretaceous-Palaeogene rocks (Hollis *et al.* 1997). There are two formations — Garden Cove and Tucker Cove. The former is 30–100 m thick and consists of detrital conglomerate, sandstone and mudstone deposited in an initially non-marine environment which became marginally marine with time. This formation contains a few fossil groups, especially spores, pollen and dinoflagellates in addition to a few foraminifera and radiolarians. It is possible that the unit includes an almost complete section across the Cretaceous/

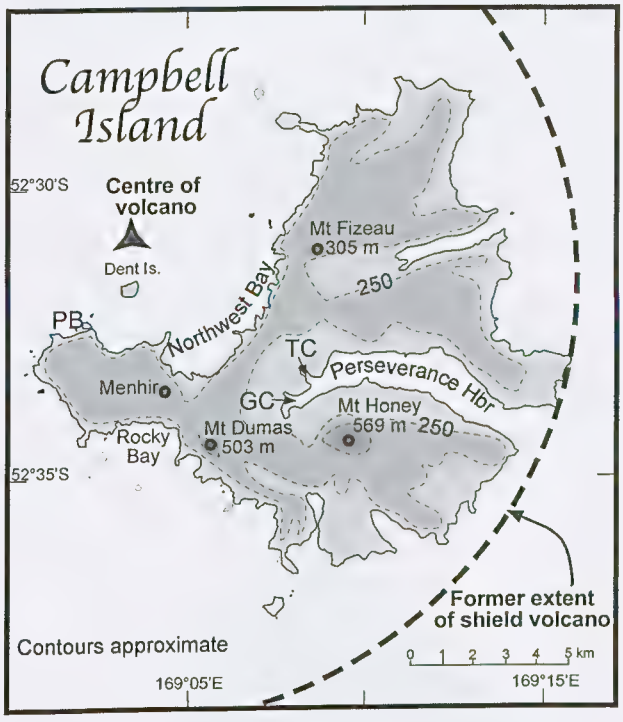


FIG. 8 — Campbell Island. GC = Garden Cove; PB = Penguin Bay; TC = Tucker Cove.

Tertiary boundary, the time when an asteroid impact led to extinction of dinosaurs and various other groups. This would be a very rare occurrence of such a section in shallow-water sediments. It is the most southerly outcrop of Cretaceous sediments in the South Pacific region (Hollis *et al.* 1997).

The Tucker Cove Formation is 100–200 m thick and consists of micritic limestone with some sand, glauconitic and nodular chert. It contains a diverse array of microfossils

of Early Eocene to Oligocene age and includes within it a Middle Eocene angular unconformity representing a short time interval. It is possible that a complete Eocene-Oligocene section exists on the island but has not been located. After deposition of the sediments, gabbro was intruded at 16 Ma (Middle Miocene) at Menhir (Morris & Gamble 1990).

The sediments (and gabbro) have acted as the basement on which the main volcano was built. The volcanic accumulation consists of lava flows and pyroclastics and the wall of Perseverance Harbour provides a good view of the low-angle volcanic sediments and lava flows. Volcanic activity is extinct and took place about 11–6 Ma, Mid to Late Miocene in geological terms. The volcanic rocks are quite diverse and include porphyritic hawaiites with phenocrysts of olivine and plagioclase. Minor trachyte and rhyolite flows also occur (Morris & Gamble 1990).

Glacial landforms are not very obvious on Campbell Island but U-shaped valleys have been interpreted and the silled entrance to Perseverance Harbour may be either glacial till or composed of debris transported by longshore currents. There is some debate about the extent of glacial evidence but McGlone (2002) recorded till and possible lateral moraine at 90 m a.s.l., and possible kame terraces, terminal moraine and erratic blocks, all suggesting considerable ice cover at the Last Glacial Maximum (18 ka). The island has suffered extensive marine erosion on the western side and this has removed much of the original volcano.

Following cessation of glaciation, vegetation became re-established at about 15 ka and similar changes to those noted on the Auckland islands are recorded at about 10 ka when tussock-grassland took over from macrophyllous forbs/herbfield. Another coeval change is noted at 7 ka when scrub vegetation developed. As with other islands on Campbell Plateau, the vegetation history is now preserved in a widespread layer of peat 1–4 m thick.

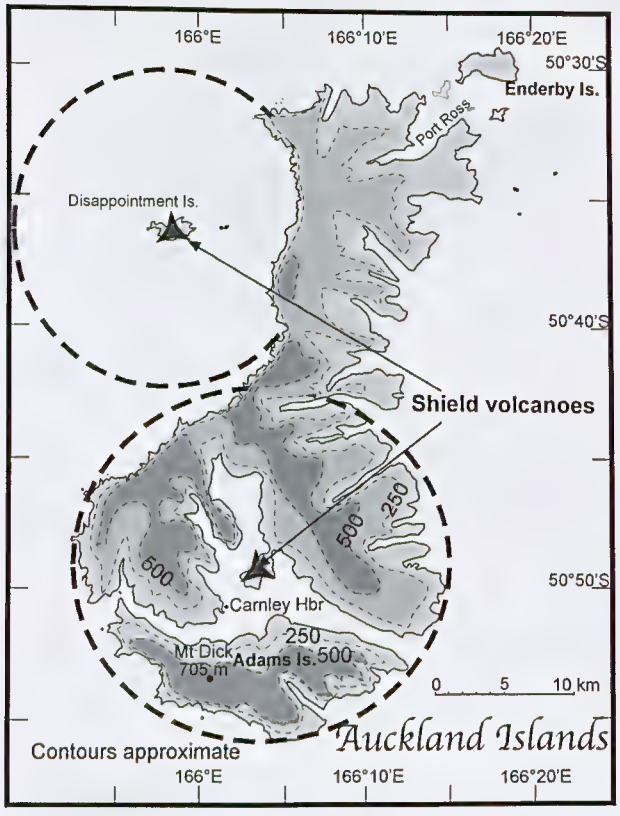


FIG. 9 — Auckland islands

Auckland islands

The Auckland islands (fig. 9) consist of the major Auckland Island but also smaller Enderby Island at the northeast and very small Disappointment Island to the northwest. The islands have a history similar to that of Campbell Island but generally earlier, and consist of remnants of two shield volcanoes sitting on continental basement which, in Carnley Harbour, includes granite and a sequence of Cenozoic sedimentary rocks (Ritchie & Turnbull 1990). The older sedimentary unit — latest Oligocene-Early Miocene Camp Cove Conglomerate 501–25 m thick — was deposited as a debris flow in a fluviatile environment and consists of matrix-supported clasts, mainly granitic. This is overlain by shallow marine Musgrave Formation about 15 m thick which has a diversity of rock types — quartz sandstone from a quartz/feldspar source, limestone and a significant fossil fauna of bivalves, gastropods, brachiopods, echinoderms, bryozoans and foraminifera. This is Middle Miocene in age.

The Auckland Island complex (Gamble & Adams 1990b) is the remnant of two shield volcanoes built on the older continental foundation. The southern of the two volcanoes is quite well-preserved, centred on Musgrave Peninsula in Carnley Harbour and its topographic outline is clear. The northwestern volcano was centred at Disappointment Island and is severely excavated on its western flank (similar to the situation at Campbell Island) and only the eastern part is preserved. Volcanism appears to have begun in the latest Oligocene (about 23.8 Ma) with younger volcanics and dyke intrusions continuing until the Middle Miocene (16.5 Ma).

Auckland Island was essentially ice-covered during the Last Glacial Maximum, and possibly several other times during the Late Cenozoic, and the eastern side of the northern volcano has suffered greatly but particularly at the Last Glacial Maximum some 18 ka. This has generated a series of marked deeply-incised fjords carved by glaciers flowing to the east. U-shaped valleys, hanging valleys, cirques at 250–300 m and moraine-dammed lakes are relics of this phase. As at Campbell Island, marine erosion resulting from heavy seas from this direction, has affected the western side of the complex more than the east which has been relatively protected and thus retains the best evidence of its glacial past.

Following the Last Glacial Maximum, vegetation re-colonised the region from about 15 ka and later vegetation changes occurred at 10–12 ka, 7.5 ka and 4 ka when various vegetation types advanced as climate ameliorated. That at 10–12 ka is most marked as tussock-grassland became established before the advent of small shrubs at about 4 ka (McGlone 2002). The remains of the vegetation and its record are preserved in an extensive peat layer 1–4 m thick in many places.

Enderby Island has a record of two phases of glacial deposition within the most recent glacial phase. It is very unusual in the region in having a white sand beach and dune system on its southern side, suggesting that the sand was derived from older continental rocks and brought to its current site ahead of sea level rise at the termination of the Last Glacial Maximum.

Peter I Island

Peter I Island (fig. 10) was named by Bellingshausen in 1821, but he could not land because of its forbidding cliffs and ice cover. It covers some 154 km^2 and is slightly elongate north-south with a roughly straight western coast and slightly embayed eastern coast. It is similar to the Balleny islands, in sitting on a transform fault where basalt lava has found an easy way to the surface, but differs from them in that it is a simple transform arrangement and a single island; there is no chain. It appears to have been a major shield volcano about 64 km in diameter that has now sunk considerably from its original elevation (Rowley 1990). The island is poorly known because of its remoteness.

The entire structure, of which the island is the exposed part, comprises about 2900 km^3 of a large volcano on the ocean floor about 4000 m deep and the island rises to 1640 m above sea level with a small crater at its apex, approximately 100 m in diameter. The formation of this cone probably began 10–20 Ma (possibly the source of earlier age estimates of 12.5 Ma come from samples taken at sea; Bastien & Craddock 1976) on oceanic crust that is about 60 Ma. Ages of lavas from the island range from 100–330 Ka. There is divided opinion about the origin of the island; is it a hot-spot or "leaky" transform source of lava? The rocks are very different from those of Jones Mountains, the closest similar rocks on the mainland of Antarctica. Hart *et al.* (1995) regarded Peter I Island as formed from hot-spot lavas from a mantle source but the rocks differ from normal hot-spot lavas in having a high $^{207/204}$Pb signal. The transform model arises from the island's proximity to the Tharp Transform Fault (Prestvik *et al.* 1990).

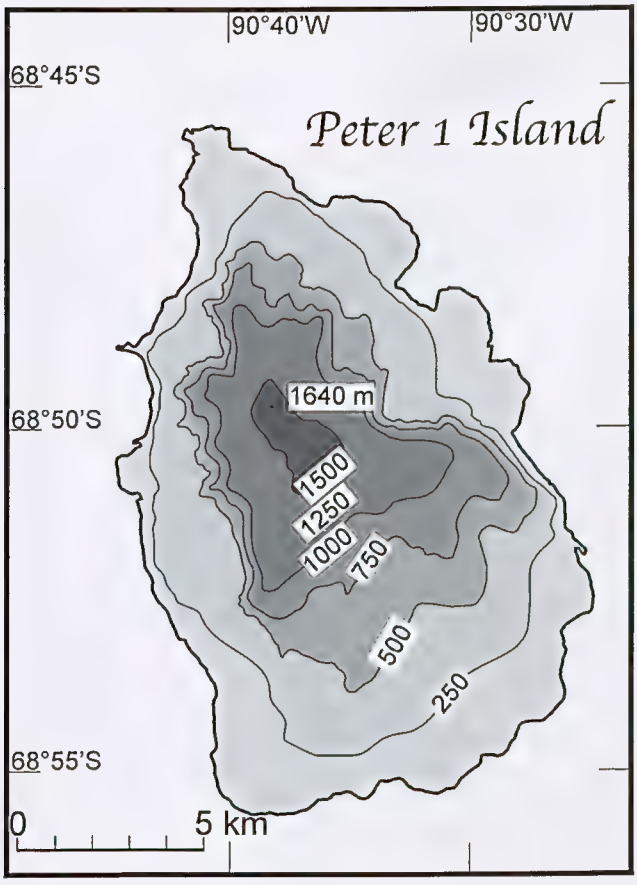


FIG. 10 — Peter I Island

The rocks consist of basalt and trachyandesite which has then been intruded by dykes and small plugs of basalt. The rocks incorporate a variety of xenoliths of gabbro and peridotite with a few of quartz rich continental crustal material. They vary from vesicular to massive and take the form of pahoehoe (ropey) lava attesting to subaerial eruption; pillow lavas, which would indicate submarine eruption, are absent.

ISLANDS WITH HISTORY RELATED TO THAT OF SOUTH AMERICA AND THE ANTARCTIC PENINSULA

The region between the southern tip of South America and the Antarctic Peninsula (fig. 11) is one of the geologically most complex areas on the earth's surface. The area includes islands such as South Georgia which is mainly continental, Shag Rocks which are continental, the South Sandwich Islands which are subduction-related, and Diego Ramirez Islands which are formed as a result of collision between the Pacific Ocean sea-floor and the continent of South America.

The structure and age of the sea-floor of the Scotia Sea west of the South Sandwich Islands has a multiphase history over a relatively short geological interval. Immediately west of the volcanic arc of the South Sandwich Islands lies a roughly north-south oriented spreading centre where the small Sandwich Plate (Cunningham *et al.* 1998) has been growing over the last 8 Ma. To the west of the new sea-floor thus formed, is older sea-floor of the Scotia Plate, due to an older episode of spreading (30–10 Ma) when South America and the northern Antarctic Peninsula separated in such a way that South America moved relatively northwest, north of a spreading ridge that was oriented northeast-southwest and subduction (now stopped) occurred under the northern margin of the Antarctic Peninsula. This plate is bounded at the west by the northwest-southeast oriented Shackleton Fracture Zone.

The Scotia Sea is bounded north and south by major transcurrent faults, the North and South Scotia Ridges with an east-west orientation. Both fault systems are marked by sinistral movement (north side relatively to the west) as South America moved west relative to the Antarctic Peninsula. Between the faults marked by the ridges, the Scotia Plate has evolved. The area involved is some 1800 x 660 km, oriented east-west.

Islas Diego Ramirez

The Diego Ramirez Islands (fig. 12A, B) consist of a few islands to 2 km long and many smaller rocky islets. Like so many of the sub-Antarctic islands, they have a northwest-southeast orientation but this is due to their proximity to the subduction zone along the Chilean margin rather than to an association with a transform fault radiating from Antarctica. They lie on the Scotia Plate south of the North Scotia Ridge and east of the Shackleton Fracture Zone.

The islands are complex geologically. In contrast with many sub-Antarctic islands, they have a long and multi-phase history (Wilson *et al.* 1991). They are part of a series of slabs of Pacific Ocean sea-floor that have accreted to the margin of southern Chile during a poorly-dated (perhaps late Palaeozoic-early Mesozoic) episode of subduction. The accretionary complex is made more complex by the presence

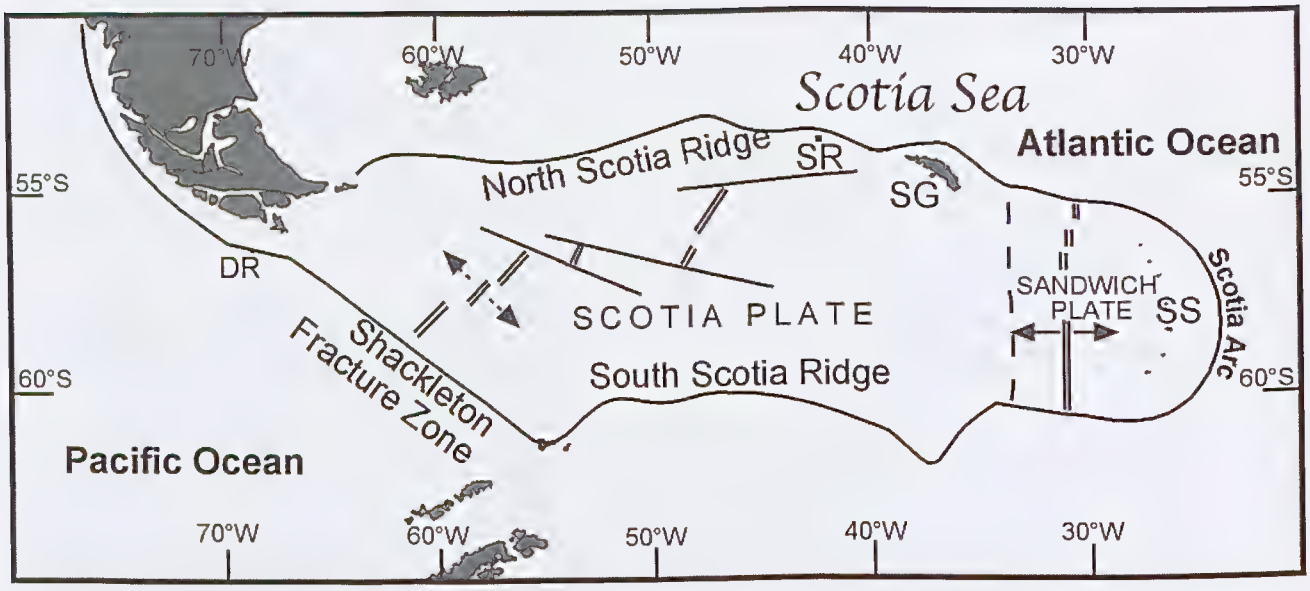


FIG. 11 — Tectonic sketch map of the Scotia Sea region. DR = Diego Ramirez Islands; SG = South Georgia; SR = Shag Rocks. Mid-ocean spreading centres shown by double parallel lines; those of the South Sandwich Plate are currently active.

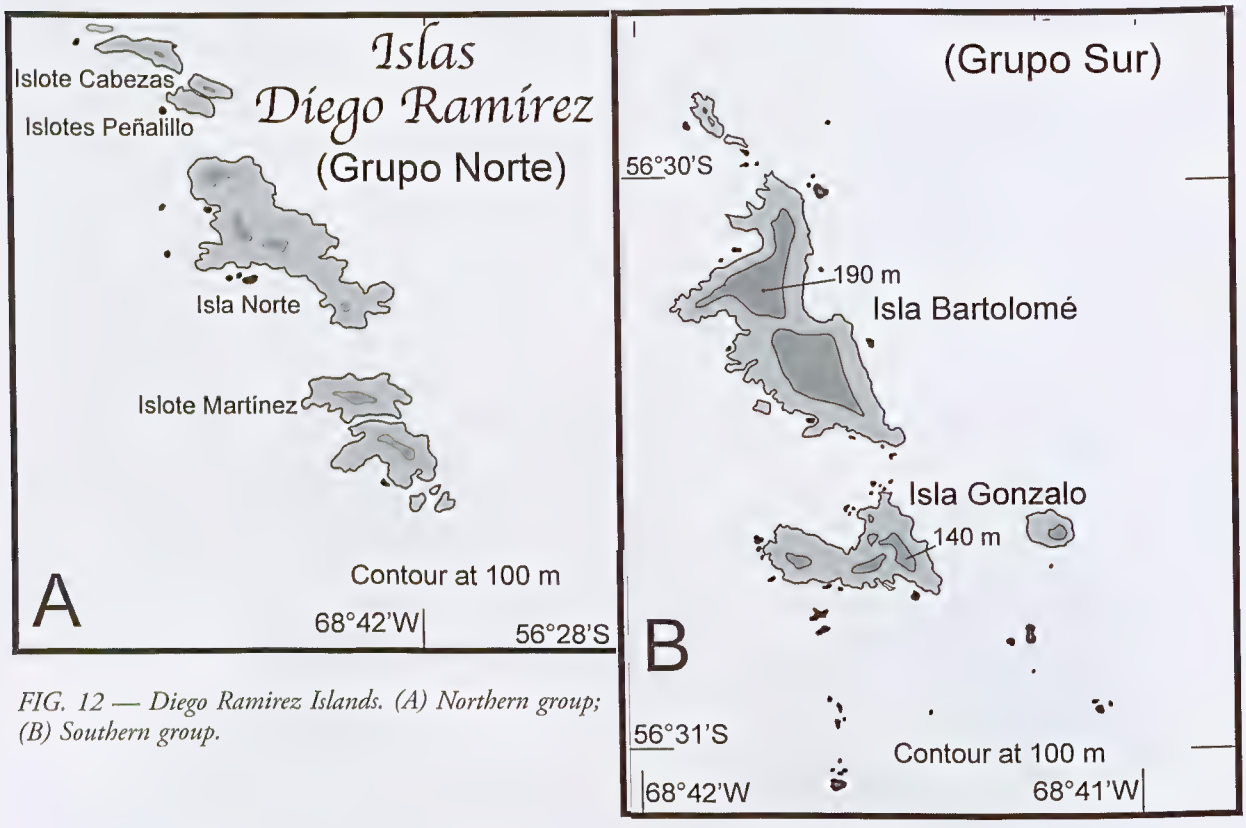


FIG. 12 — Diego Ramirez Islands. (A) Northern group; (B) Southern group.

within it of an older Pacific Ocean seamount. Dating of events is not comprehensive but it is likely that the rocks suffered their most recent major metamorphic event in the Middle Jurassic (169 ± 16 Ma) and thus the original rocks were older, perhaps even late Palaeozoic. There appear to be two rock associations. One is more complex and regional, a tectonic melange of sea-floor rocks (sediments and basalts) that were initially at the leading edge of the rocks being subduced but later rose as the arc margin rose. The lithological affinities of the rocks are with those of the distant South Shetland islands and provide a link from South America, through South Georgia and around the margins of the Scotia Sea to the Antarctic Peninsula. The other association consists of metabasalts that represent the altered remnants of the original basalt of a subduced seamount. They are shallow-water pillow basalts with abundant vesicles and diverse characteristics, typical of the variety expected in the relatively shallow-water environment around a seamount.

South Georgia

South Georgia is dominantly continental and lies on the eastern end of the North Scotia Ridge (fig. 13) which is separated from the South American Tectonic Plate by the Falklands Trough; however, Cunningham *et al.* (1998) place South Georgia on the South American Plate (their fig. 1(a), inset) whereas their fig. 1(b) indicates that gravity data would suggest that it lies on the Scotia Plate. Figure 11 follows the implication of fig. 1(b) of Cunningham *et al.* (1998). South Georgia was the site of the single "Antarctic" station for the first International Polar Year of 1882/83 — in Royal Bay (Headland 1992). The island is arcuate, concave to the southwest, and is the exposed part of a large continental basement fragment 380 x 140 km marked by the isobath at 1000 m (Simpson & Griffiths 1982) and with margin declining steeply to the 3000 m isobath. It seems that the exposed geology continues below sea level and that South Georgian rock types are typical of the entire block.

The 3000 m isobath delineates a series of three continuous but separately identifiable east-west oriented continental blocks along the North Scotia Ridge. The most easterly is the South Georgia Block and the other island-bearer is the Shag Rock Block to the west-northwest of South Georgia. Its rocks may be older than those of South Georgia.

South Georgia, like the islands on distant Campbell Plateau, on the mirror side of the East Pacific Spreading Centre, are fragments of the older continental crust of Gondwana left behind during the dispersion of the supercontinent. South Georgia and some other islands such as the Diego Ramirez Islands off southern Chile have been formed, or affected, by collision of Pacific Ocean sea floor with the continental rocks of South America. South Georgia is one of the most spectacular places on Earth but early explorers such as Cook were not full of praise as they referred to its forbidding appearance. It is an extremely rugged landscape.

The island can be divided into two distinct terranes. One is the major part and the second, smaller, area is that in the southern reaches of the island — the Drygalski Fjord Complex of the Salvesen Range and to the southwest.

The major part is composed of strongly folded Late Jurassic and Early Cretaceous sedimentary rocks, mainly sandstones and volcanic rocks allocated to two major formations — Cumberland Bay and Sandebugten. These formed in a back-arc basin behind the southern Andes while subduction occurred on the southwestern side of the continent. The eastern side of the basin would have been parts of continental South America. The Cumberland Bay Formation which is the dominant exposed unit is Early Cretaceous in age (Aptian, 100–110 Ma; Thomson & Tanner 1982) as judged by sparse bivalve and ammonite fossils, composed of andesitic volcaniclastic greywackes (Tanner 1991) up to 8 km thick. It was deposited in a marine environment by turbidity currents carrying sediments in units up to 5 m thick, from volcanic islands west of the current island. The composition of the greywackes is consistent with this scenario.

The Sandebugten Formation is significantly different in composition, has thinner sedimentary units and is composed of siliciclastic turbidites sourced from the more easterly side of the same sedimentary basin and thus more continental in character. It occurs mainly in the northeastern edge of the island around Barff Peninsula east of Grytviken. There is doubt about the age equivalence of the Cumberland Bay

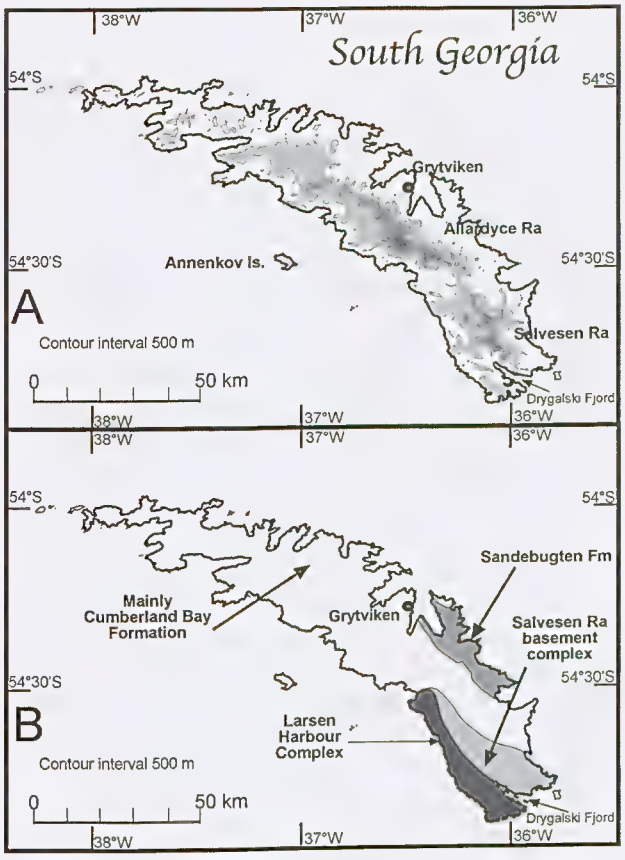


FIG. 13 — South Georgia. (A) Topography; (B) Geology.

and Sandebugten Formations as fossils are sparse especially in the latter formation. It is possible that the Sandebugten Formation is considerably older than the Cumberland Bay Formation.

There is uncertainty about the relationship between the two formations. A thrust is normally evident between them but whether this is simply a thrust or also marking the position of an unconformity is not clear. The two formations have suffered different post-depositonal histories. It seems (Tanner 1991) that deformation of the formations occurred separately before they came into thrust relationships, the deformation of the Sandebugten Formation occurring earlier, and that of the Cumberland Bay Formation coinciding with the thrusting during the mid-Cretaceous at 91–82 Ma (Thomson & Tanner 1982).

The rocks of Annenkov Island are part of this sedimentary sequence but are only 3 km thick and have more abundant and diverse, but less definitive fossils which can be determined only as Early Cretaceous (Thomson & Tanner 1982).

The Salvesen Range is composed of Gondwanan continental gneisses and schists of the Drygalski Fjord Complex that are intruded by granite, layered gabbros and basic dykes (Headland 1992). These are the oldest rocks on the island and are the remnants of the original continental block on which the sedimentary sequences were deposited.

Immediately to the west of the Salvesen Range is the Larsen Harbour Formation, the boundary coinciding with Drygalski Fjord. Here are pillow lavas, radiolarian cherts, sheeted dykes (as occur on Macquarie Island), gabbros and a complex association (ophiolite suite) typical of that constituting the sea-floor. These rocks have been plastered

onto the continental rocks during a period of subduction along what was the Pacific Ocean margin. Instead of being consumed during subduction, these rocks have remained above sea level and may have over-ridden the older basement. As the Pacific sea-floor was subduced along the southern margin, folding was intensified and a slice of Pacific sea floor, instead of being led down, attached itself to the southern margin of the island through obduction. Thus South Georgia is basically a piece of South America with a slice of Pacific Ocean sea-floor attached as Drake Passage was formed.

The island has 13 peaks reaching over 2000 m, the highest Mt Paget at 2934 m a.s.l. This ensures that, even if north of the Antarctic Polar Frontal Zone, the island is heavily glaciated and has been for many millions of years. The island bears the scars of this history. Ice reaches to 200 m on the southwest and 400 m on the other side of the island. The coast is thus heavily indented by fjords; it is marked by high cliffs in most places.

The small area of Shag Rocks (also known by a variety of other names and locations in earlier history) is some 250 km northwest of South Georgia. The rocks, while continental, are different in type from South Georgia. These are greenschist facies metamorphic rocks that form small very rugged, triangular outcrops whose outcrop shape is controlled by internal structural fabric. Maximum elevation is 71 m.

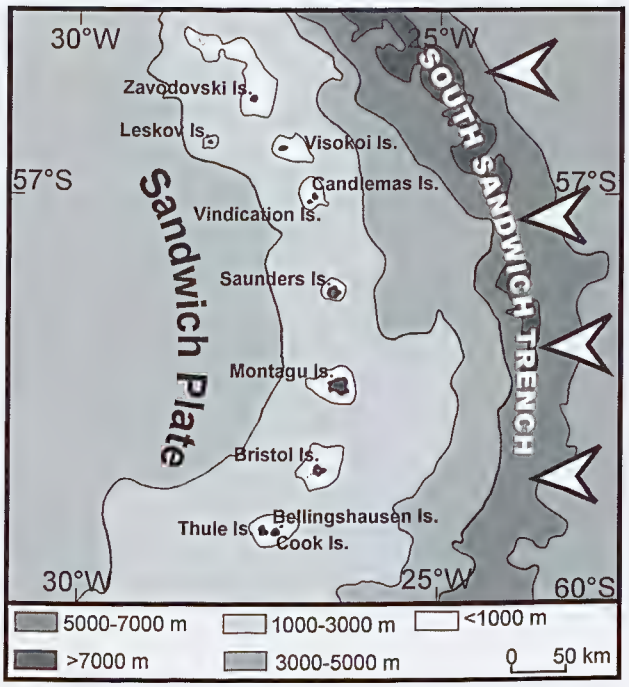


FIG. 14 — South Sandwich Islands. Direction of subduction indicated by large arrowheads.

THE SCOTIA ARC/SOUTH SANDWICH ISLANDS

The Antarctic tectonic plate has almost no area subject to subduction, but there is one relatively small but important area where this aspect is well developed — the South Sandwich Islands — 10 volcanic islands and a noteworthy shoal (fig. 14) over an arcuate length of 350 km; most have been active in the period of European visitation (Barker 1990). Barker (1990) recorded no Holocene eruption on Montagu Island, but Patrick *et al.* (2004) provided evidence for new activity in 2002 and continuing. Along Scotia Arc, the South Atlantic sea-floor is being subduced as a narrow slab in a "simplest of the world's arc-basin systems" (Leat *et al.* 2004) from the east below the South Sandwich Plate, accompanied by development of a volcanic arc with typical active volcanoes compositionally different from those elsewhere on the plate, and where deep earthquake activity is very pronounced. Even though the system is "simple", there are marked differences between the northern and southern ends of the arc. The northern end has a complex zone of seismic activity in contrast to the southern end which coincides with a transform fault. The eastern half of the Sandwich Plate and the Atlantic sea-floor converge at 67 (north)–79 (south) mm/year. The South Sandwich Trench, only some 100 km to the east of the volcanic arc, is over 8000 m deep in places, by far the deepest water in the Antarctic or sub-Antarctic. From the trench, the subduction zone dips at 75° to the west at 60 km depth and can be traced to depths in the mantle of only ~180 km and thus may be a geologically young feature, 15 Ma according to Leat *et al.* (2004). As expected in a volcanic arc above subducing crust and lithosphere, the rocks are generally pyroclastic in stratovolcanoes and with composition, while variable and including basalt, tending more into the andesite/dacite area with higher silica and volatile content, higher viscosity and evidence of more explosive volcanic activity. Eruptions include occasional release of very noxious gases, such as that encountered by Capt. C.A. Larsen from Zavodovski Island, and accompanied by explosive volcanism such as that which produced an immense raft of pumice from the previously unknown Protector Shoal at the north in 1962 (Gass *et al.* 1963, Sutherland & Olsen 1968). Lavas from this site seem to come from a variety of sources, not a single parent (Leat *et al.* 2007). Over the last 200 ka, five eruptions have produced material that has been incorporated in the ice at Dome C in East Antarctica (Narcisi *et al.* 2005).

The slab of subducing South Atlantic sea-floor is older in the north (83 Ma) than in the south (27 Ma) and carries into the subduction zone the sediment that has accumulated on it; all sediment seems to be carried down (Leat *et al.* 2004) but that in the north has a higher carbonate content than that in the south.

The islands are roughly evenly spaced along the arc, about 70 km apart. Leskov Island is about 50 km west of the axis of the other islands but this seems not to constitute evidence for any major anomaly. They are generally small, stark, barren features only 2–12 km across; the largest islands (Montagu and Saunders) are in the centre of the chain but there is no systematic variation in size along the chain. Visokoi, Montagu, Bristol and Cook islands are over 1000 m high, and Saunders Island 990 m. Others are substantially lower. Many are roughly quadrate but Leskov, Saunders, and to a lesser extent Thule, are arcuate and concave to the northeast or east. Protector Shoal reaches to within 27 m of sea level. The islands generally sit atop larger subsea volcanic foundations that may be 30–50 km wide.

Most islands are single volcanoes but Candlemas Island is divided by low sand flats with lagoons into two distinct volcanoes, a highly dissected younger cone in the northwest centred on Lucifer Hill, and an ice-covered older southeastern roughly symmetrical quadrate remnant. The younger lavas are andesite and dacite with low K_2O in contrast with the porphyritic basalt of the older sequence. Leskov Island and Protector Shoal have high silica content lavas, 67% in the case of Protector Shoal.

The age of most islands is Holocene but Montagu Island is dated at about 1 Ma, and Freezland Rock off the southwestern end of Bristol Island is 3 Ma. The entire arc has been estimated to be 5 Ma (Barker 1990) and there seems to be no systematic variation in age along the chain.

The islands are all glaciated but vary greatly in ice cover, the difference depending on elevation, the proportion of the island that is elevated, and also on the heat flow from eruption in active volcanoes.

Bouvetøya

Bouvet Island (fig. 15) lies very close to the triple junction of three tectonic plates — South American, African and Antarctic. It is a little to the east of the triple junction near the Southwest Indian Ridge and a little south of the Ridge where it formed. It consists of a single dominant cone with summit caldera that is open to the north, possibly due to collapse of the northern flank of the volcano. The northern, western and southern margins are relatively straight. The north and west coasts are steep, the north due to collapse, and the west due to marine erosion, but elsewhere the slope from the caldera rim to the coast is uniform and thus the volcano appears to be more shield-like than a stratovolcano. The concavity left by the collapse to the north is now filled by the island's major glacier, the north-flowing Posadowskybreen. The rest of the island is covered by an icecap.

Because the island is so close to the triple junction and because the triple junction is believed to mark a long-lived plume marking the location where Antarctica, Africa and South America separated at some 120 Ma, the island volcanic rocks have been subject to many studies over a considerable interval, despite the difficulty of access (Verwoerd 1990a). Such studies have focused on questions of long-term evolution of hot-spot magmas especially at a point where there is no chance for involvement of a continental crust component.

The volcanic rocks are dated at slightly over 1 Ma and they sit on older crust — some 4.5–5 Ma which has had a single, geologically short history of two intervals. The first sequence includes dominantly pyroclastics which have been altered by the influence of seawater on the erupting rocks. The second sequence formed above sea level away from marine influence and consists of subaerial basalt flows consistent with the appearance of a shield volcano.

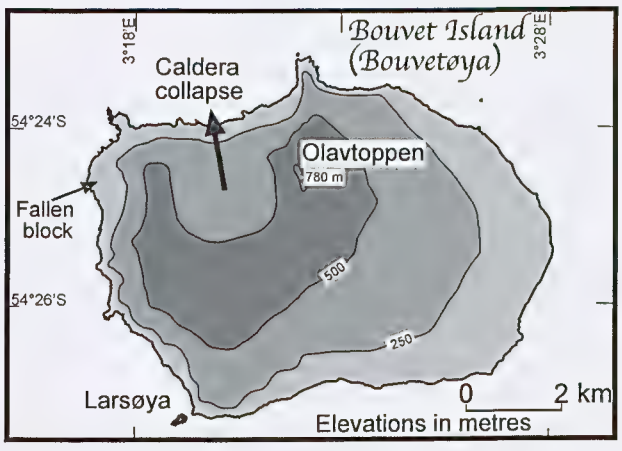


FIG. 15 — Bouvetøya

The rocks lie close to the boundary between tholeiitic and alkaline fields (fig. 3) but slightly on the alkaline side, and while dominantly hawaiite extend as far as trachyte and alkali rhyolite. The rhyolites come from Larsøya at the southwestern point of the island and may be the youngest lavas of the area.

Between 1955 and 1958, a new beach and raised platform developed in the northwestern part of the island. Initially this was thought to be evidence of a modern eruption but re-examination shows that the rock is 0.45–0.5 m.y. old and the block retained its internal cohesion and thus is due to simple downslope landslide movement and not a chaotic avalanche or modern eruption. Thus there is no evidence of modern volcanism even though there is mild fumarolic activity at the summit.

Gough Island

Gough Island (fig. 16A, B) lies at about 40°S and is thus closer to the equator than to the South Pole but is taken as sub-Antarctic for the purposes of the Scientific Committee on Antarctic Research (SCAR). It is the western end of three features — the others are McNish and R.S.A. Seamounts (fig. 16A) — which probably formed in the same way as Gough Island on a transform fault offset from the Mid-Atlantic Ridge, immediately south of Walvis Ridge. Between them, they constitute the Gough Fracture Zone (Chevallier 1987). There is some controversy about its geological setting but Gough Island seems to be similar to the Balleny islands except

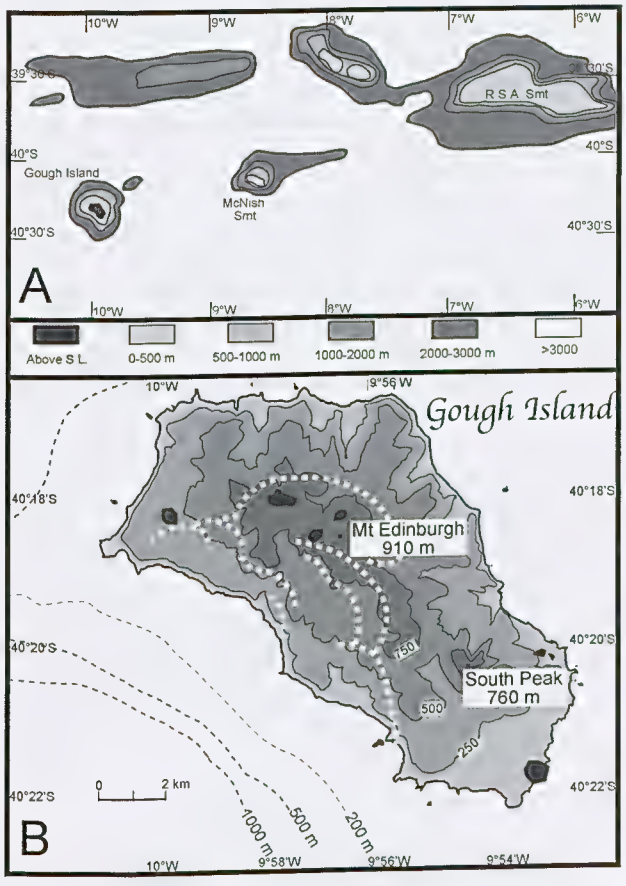


FIG. 16 — Gough Island. (A) The regional setting. (B) Geology of Gough Island. Dashed white arcs indicate past calderas; black spots trachyte stocks.

that two of the three island/seamount structures have already sunk below sea level thus leaving Gough Island as the lone island expression of the chain.

Gough Island is a single volcanic complex (Chevallier *et al.* 1983, Chevallier 1987, Maund *et al.* 1988) but with several episodes in its short history. When the entire edifice above and below sea level is considered, it is roughly circular in plan, but the island itself is elongate northwest-southeast, about 13 x 6 km, and slightly concave to the southwest. Chevallier (1987) recognised six stages in the volcanic history of the island. The oldest basaltic volcanism occurred at a little over 1 Ma at about sea level and even included beach pebbles in the 70 m thick volcanic unit which shows evidence of explosive activity related to the interaction of sea water with the lava. This unit is exposed mainly on the northeastern side of the island. This was followed by basalt eruption above sea level from the main body of the volcano, 1 Ma at the base of the sequence. These lavas cover a little over 50% of the surface of the island, mainly in the centre and southwest and are cut by a series of many radial dykes. After an erosive phase, a series of basalts were extruded about 3 km southeast of Mt Edinburgh at 0.5–0.6 Ma. This ended the basaltic phase of the island's history and is further marked by the collapse of the central caldera. During the interval 0.47–0.12 Ma, trachyte intrusion and extrusion filled many of the valleys formed after the basaltic phase and produced a series of trachyte plugs at various points around the island. This phase is centred on Mt Edinburgh (910 m), but these rocks are not cut by dykes. The latest eruption may have occurred as recently as 2300 years ago. The lava arose from a hot-spot source (Harris *et al.* 2000) but in contrast to Tristan da Cunha to the north, the lavas have risen to the surface without any mixing with sediments along the way and constitute a closed fractional crystallisation system.

A marked feature of the island's volcanic centres is the presence of a series of arcuate, concave to the southwest, crater rims marking the positions of successive volcanic centres. It is likely that the southwestern side of volcanoes has suffered periodic collapse to the southwest generating the concave-to-the-southwest aspect of the island.

The island appears to be devoid of evidence of glaciation but it does show signs of progressive elevation during its growth (Gribnitz & Kent 1989). Well-developed terraces occur at 3–4 m, 12–15 m, 30 m, 55 m, 75 m, and at –23 and –50 m. It has been suggested that that at 3–4 m level relates to coastal erosion at 120 ka (the last interglacial); those at 12–15 and 30 m to the Middle Pleistocene; that at 55 m earlier in the Pleistocene, and the 75 m level somewhat older. Those below modern sea level may relate to intervals of lower sea level during the last glaciation.

TECTONIC EVOLUTION OF THE INDIAN OCEAN AND FORMATION OF INDIAN OCEAN ISLANDS

The Indian Ocean is unusual in having a series of submarine plateaux — large areas of ocean floor at intermediate depths and usually sampled as volcanic rocks formed subaerially and now sunk below sea level. These submarine plateaux support volcanic islands such as Heard Island and Îles Kerguelen on Kerguelen Plateau, and Îles Crozet on Crozet Plateau. Many of these islands, instead of having formed in one simple, short interval, have several episodes in their history over many tens of millions of years. Heard Island and Îles Kerguelen are consistent with this remark but there are exceptions.

The major tectonic development affecting the Indian Ocean began at 115–125 million years (early Cretaceous) when Africa-South America split off from Gondwana, opening up the Weddell Sea (Royer & Sandwell 1989, Royer & Coffin 1992). Shortly after this time, India (or what geologists term Greater India) began to move north from Antarctica from Gunnerus Bank, around Enderby Land to the Windmill Islands, thus initiating the Indian Ocean and permitting marine conditions to enter along this long coast. At about the same time, Africa/South America started to move apart allowing the Atlantic Ocean to form.

The northward movement of India also coincided with the initiation of a Large Igneous Province (LIP) which led to the formation of the Kerguelen Plateau (Duncan 2002, Frey *et al.* 2003, Quilty 2006). Because of its size, and as a high proportion of the Kerguelen Plateau lies below sea level, it is not well sampled except on the few islands and through deep sea drilling. Its history cannot be said to be well understood. It formed in three distinct, short-lived stages — at about 118–119 Ma, 100–95 Ma, and 35 Ma and younger. Initially this included what is now Broken Ridge and all was attached to southwestern Western Australia. The first phase of disintegration was marked by vast outpourings of basaltic lava above sea level in a short interval followed by formation of soils, supporting vegetation of palms and ferns recovered by drilling of the Ocean Drilling Program (ODP) in 1988 (Mohr & Gee 1992, Francis & Coffin 1992). It may also have been a major source of carbon dioxide (Frey *et al.* 2003) with Greenhouse effects (Hansen *et al.* 2007). It is also likely that a thinned fragment of continental crust remains under Elan Bank, west of the main body of Kerguelen Plateau, and evidence of a continental component elsewhere on the plateau was encountered during drilling by ODP Leg 183 in 1999 (Ingle *et al.* 2002). The foundations of Kerguelen Plateau were laid. This piece of Kerguelen Plateau sank below sea-level at about 100 Ma and has been accumulating pelagic sediment and volcanic material ever since, interrupted by times of increased ocean flow over the Plateau eroding some of the material already deposited and generating gaps in the geological record.

The second phase in Kerguelen Plateau formation occurred at about 100–95 Ma (late Cretaceous) when Central Kerguelen Plateau was formed; this supports Heard and McDonald islands which did not come into existence until much later. This part of the Plateau had a similar history to that of Southern Kerguelen Plateau, but is later. Until this time, part of the sea-floor spreading was occurring north of Kerguelen Plateau which remained on the Antarctic Plate, and a second coeval phase was active along the Western Australian coast opening up the eastern Indian Ocean. India kept moving north, generating sea-floor behind it and eventually colliding with Asia at about 40 Ma to form the Himalayas; this continues today.

This 100–95 Ma event probably coincided with the commencement of the northward migration of Australia, allowing the Indian Ocean to penetrate between Australia and Antarctica, but this sea-floor spreading initially was very slow and the southward projection of Tasmania and thinned oceanic crust south of it (now South Tasman Plateau but two separate fragments at the time) prevented any oceanic flow from the Indian to the Pacific Ocean south of Australia. The extension of this spreading ridge led to Australia and Antarctica being on separate tectonic plates. No circum-polar

circulation yet existed but there may have been some flow through the Antarctic Peninsula region, some of which did not exist at 100 Ma. Sea-floor spreading between Australia and Antarctica accelerated to the modern rate of 7 cm/yr at 55 Ma, and by 34 Ma enough had occurred to allow circumpolar circulation to develop as the gateway between Australia and Antarctica grew wide enough.

At this time, the South East Indian Ridge (SEIR) between Australia and Antarctica began to split Kerguelen Plateau from Broken Ridge, generating new sea-floor between Kerguelen Plateau and Broken Ridge/Australia. The rift was now complete. Antarctica lay isolated over the South Pole while all other, now individual, fragments of Gondwana moved northward.

The northern part of Kerguelen Plateau formed at about 40 Ma and Îles Kerguelen began a complex evolution of basaltic volcanism interspersed with intervals of forestation forming horizons of sediments with peat and fossil trees between lava flows. Volcanic activity was more or less continuous from about 26 Ma (latest Oligocene) to very recently. The region is now quiet.

Marion and Prince Edward islands — the Prince Edward Islands Group

Marion and Prince Edward islands (fig. 17) sit atop a small submarine plateau — the Marion Plateau, mostly shallower than 200 m (and thus much exposed during the low sea level of the Last Glacial Maximum) some 55–60 km long, oriented north-northeast - south-southwest, which formed at about 54 Ma (Verwoerd 1990b). They occupy positions at opposite ends of the plateau. They have a relatively short, dominantly volcanic history, with episodes of marine sedimentation, similar to the case in several other Indian Ocean volcanic islands. McDougall *et al.* (2001) regarded the volcano as related to hot-spot activity and recorded a track of a hot-spot (the Marion Hot-spot) over the last 120 Ma from east of Madagascar to the current position of the islands.

Marion Island is slightly elongate east-west with a gentle dome shape, strong radial drainage and, in contrast to many islands discussed here, lacks a steep-cliffed margin.

Two main periods of eruption are recognised as (McDougall *et al.* 2001) "older grey lavas" and "younger black lavas". The former does not outcrop widely as it has been covered by the more recent black lavas. The "older lavas" were extruded between 450–30 ka and alternate with sediment horizons many with glacial features. Five (perhaps as many as eight) glacial intervals are recognised and have been dated between dated flows. Flow dates are 454–413, 363–323, 244, 201–156, 110, 92–81 and 50 ka. The glacial intervals are then centred roughly on 450, 275, 190, 75 and 25 Ma, and have been interpreted as relating to well-known glacial maxima as defined by ice and sediment records elsewhere on Earth. Other possible glacial sediments are at 340, 122 and 100 ka. The younger black lavas all seem to be 10 ka and younger in age and are fresh and little-altered. The modern volcano on Marion Island erupted along an east-west fissure in 1980 and the most recent eruption was in 2004/2005. There is much evidence of activity in the last few thousand years from some 150 volcanic cones scattered widely around the island with little evidence of any structural pattern.

All lavas are attributed to the alkali oceanic island basalt group but lack any deep-seated xenoliths. Trachyte occurs on

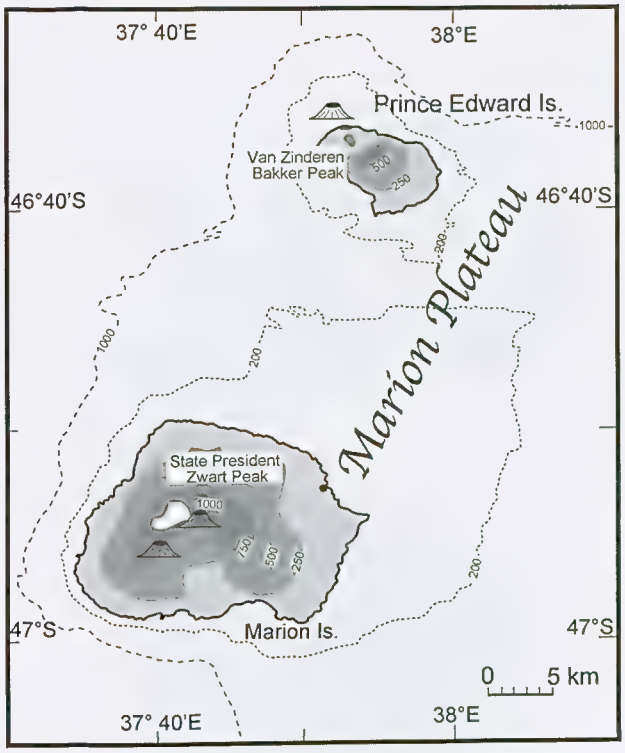


FIG. 17 — Marion Plateau with both Marion and Prince Edward islands.

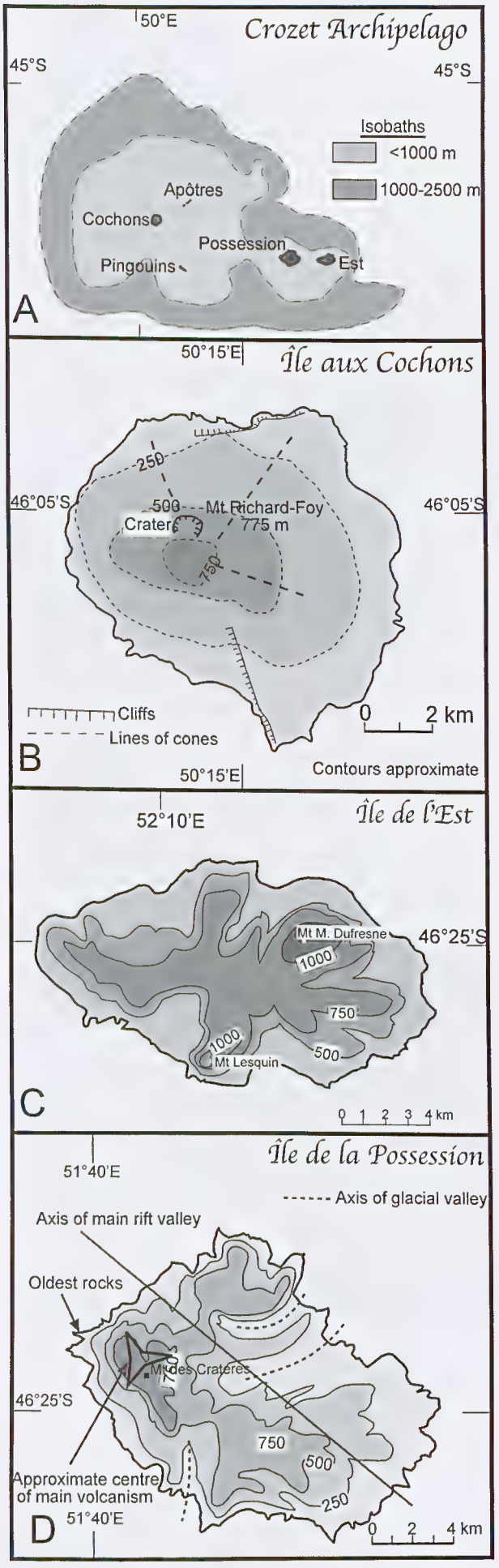
Prince Edward Island. Gravity-controlled slope failure and landslides have had a major control on the modern landforms of the island leading to the rather uniform slopes.

Prince Edward Island is significantly smaller than Marion Island but was larger in the past. In contrast to the gentle slopes of Marion Island, it is marked by a 400 m escarpment at the coast on the northeast and southwest, but well inland elsewhere. The escarpment close to the coast marks the position of faults that caused collapse of the island margins along the northwest-southeast trend. Prince Edward Island has similar lavas to those on Marion Island but also includes more silicic lava (trachyte) with eruption mainly in the 200–110 ka interval. Verwoerd (1990b) suggests the lavas on the two islands come from different reservoirs. In addition to the main vent at the peak, there are about 15 cones widely scattered over the island; some of these are believed to have been active during the Holocene but no modern eruptions are known.

Marion Island has a small icecap above 1100 m and was seriously affected by glaciation during the Last Glacial Maximum; the moraines left by this glaciation are concentrated on the southeastern and northeastern extremities of the island. Prince Edward Island may have missed that glacial influence by virtue of being farther north and of lower elevation. Much of Prince Edward Island has disappeared, probably to the northwest, either by horizontal movement along a fault, or by a catastrophic slump that characterises many oceanic islands.

Îles Crozet

This series of islands has a western and eastern group and all are incorporated in the Crozet Archipelago (fig. 18). They sit on Crozet submarine plateau on the eastern flank of the Indian Ocean Ridge which passes between South Africa and



Antarctica (Nougier & Thomson 1990a, Chevallier *et al.* 1983). The plateau could be as old as 54 Ma but the islands are made of much younger volcanoes. The northeastern margin of the plateau has a marked 135° azimuth and this is reflected in the orientation of the long axis of Île de la Possession and its central rift, the orientation of faults and cones on Île aux Cochons, and many other aspects of the islands. The western group of three islands (Île aux Cochons and the much smaller Île des Pingouins and Ilôts des Apôtres) and the eastern island group (Île de la Possession and Île de l'Est) are composed of many small volcanoes some of which have been active in the last few thousand years. The larger islands have all been affected by glacial activity which has sculpted many into their present landforms but there are no glaciers currently on the islands.

While the islands may be widely scattered on the submarine plateau, some phases of volcanic activity are consistent across the chain. Activity in the eastern group is from 9–1.3 Ma, but between 1 and 0.5 Ma all islands in the archipelago have been active.

Île aux Cochons is a single young volcano, less modified than others in the area, and steeper on its western side. It has grown through two phases of activity — the first represented by 400 m of phreatomagmatic breccias (caused by the explosive interaction of lavas with ground water) and interbedded 1 m thick basalt flows exposed in cliff sections in the northern and southern parts of the island. This phase (1–0.5 Ma) was followed by faulting which allowed emergence of the second phase (0.2 Ma – present) of some 60 small cones and flows radiating from a crater at the summit (Mt Richard-Foy). The younger cones commonly are arranged in four radiating linear series along the earlier, post first-phase faults. Two of the directions (70° and 160°) are parallel to faults that control some of the coast directions indicating that the coast is also partly fault-controlled. These phases are the youngest recorded in the archipelago and other volcanoes have evidence of earlier eruption. The lavas are all alkali basalts.

Île des Pingouins and Ilôts des Apôtres are 50 km south-southeast and 15 km northeast of Île aux Cochons. Both are remnants of volcanoes but have been severely reduced in size by block faulting or erosion. Île des Pingouins displays coarse breccia, flows and hyaloclastites (glassy fragmental lavas) in cliffs, and Ilôts des Apôtres consist of two small islands and 12 rocky islets arranged along the 70° azimuth.

The eastern group comprises two older and larger volcanic islands (Île de la Possession and Île de l'Est) which may still technically be active. Île de la Possession is a stratovolcano which has dates of 8.1–0.53 Ma and was formed during five or more phases of volcanic activity. The oldest rocks occur on the western tip of the island and consist of fossiliferous hyaloclastite with mussels and pectenids (Chevallier *et al.* 1983) deposited in a shallow marine environment. Preservation is too poor to allow accurate radiometric dating. The second phase provided the 8.1 Ma date and was the main stratovolcano-building event that developed the basement of the island. The lava source probably was on the western side of the current island and generated lavas and interbedded pyroclastics until 2.7 Ma. The centre of the entire activity was to the west of the island. Immediately following this

FIG. 18 — (A) Crozet Archipelago; (B) Île aux Cochons. (C) Île de l'Est. (D) Île de la Possession.

phase, the volcanic pile was intruded at about 1.3 Ma by extensive ring dykes and lesser cone sheets. The third phase consists of coarse conglomerates and other detrital material 10–50 m thick, overlain by lavas and sills. The lavas were fed by large radial dykes with a centre on the western side of the island. Dates derived from this phase are in the range 1.03–0.72 Ma. The island then underwent a period of rifting along 135° to produce a rift 5 km long and 12 km long, and extends beyond the island as part of re-activation of a much older feature. Volcanism from this phase occurred between 0.7–0.53 Ma and produced a 10-m-thick plateau of basalt which covers much of the island. Rocks of this phase were then modified by glaciation which produced three large U-shaped valleys. The final phase recognised so far consists of the products of some 30 small cones older than 5.5 ka. Structural modification of the entire complex during this time is probably related to regional rather than local tectonism.

Île de l'Est is oriented east-west, at variance with the dominant 135° trend so common in other features of the archipelago. Its basement consists of a metamorphosed 8.75 Ma complex of gabbro (and related rocks) which has been cut by dykes, many with orientations of 110–135° (as widespread on the Archipelago and parallel to a nearby prominent sea-floor magnetic anomaly) as sources of lava for the succeeding four phases of volcanism which produced a 1000-m-thick sequence of agglomerates and lesser flows. Successive volcanic episodes were focused on the centre of the island to produce a high stratovolcano. The second phase began with a basal conglomerate succeeded by agglomerate and thin flows, followed in turn by thick agglomerate and basalt lava flows. The final phase consists of a few scoria cones dominantly in the eastern end of the island. Île de l'Est lavas appear to be the most diverse of those known from the Archipelago and the basement contains the only such rocks known from the Archipelago.

The island has been subjected to severe glacial erosion which has produced a series of radially arranged valleys and a major cirque complex with related moraine on the southwestern side.

Amsterdam and St Paul islands

Each of these islands, some 100 km apart, lies about 15 km southwest of the axis of a northwest-southeast oriented spreading ridge in the western Indian Ocean and thus is important for the study of ridge-crest volcanism. A northeast-southwest oriented transform fault appears to pass between the two islands. The islands are less than 0.4 Ma in age and the Amsterdam-St Paul Plateau less than 5 Ma (Doucet *et al.* 2004). The hot-spot that was parent to the Plateau is now believed to lie below Boomerang Seamount.

Amsterdam Island (Nougier & Thomson 1990c) is a dormant stratovolcano bounded on its northwest and southwest flanks by fault-controlled cliffs (fig. 19). The controlling cliffs are partly parallel to the axis of the parent ridge crest. Nougier (1982) recognised two volcanic phases in the history of the island. The older volcano (perhaps 0.1 Ma) was the main construction event and is referred to as the Fernand palaeo-volcano with its feeder dyke at Pointe d'Entrecasteaux, a small protuberance on the southwestern side of the island. The eruption products of the older volcano are porphyritic basalt with plagioclase and clinopyroxene phenocrysts, and some aphyric lavas.

The younger volcano (the Dives neo-volcano) had an eruption centre about 2 km east of the earlier Fernand palaeo-volcano. Initial lava flows were to the west but later to the north with flows to about 3 km long. Eruptions always seem to have been non-explosive. The age of the Dives neo-volcano is unclear but seems to have been in the last few tens of thousands of years. There are some 20 later small scoria cones, some of which may have erupted in the last 100 years producing glassy lavas. The dominant lavas contain plagioclase phenocrysts that are richer in the anorthite end member, suggesting an evolution in lava type towards the Ca end member. Such lavas are aphyric farther away from the source.

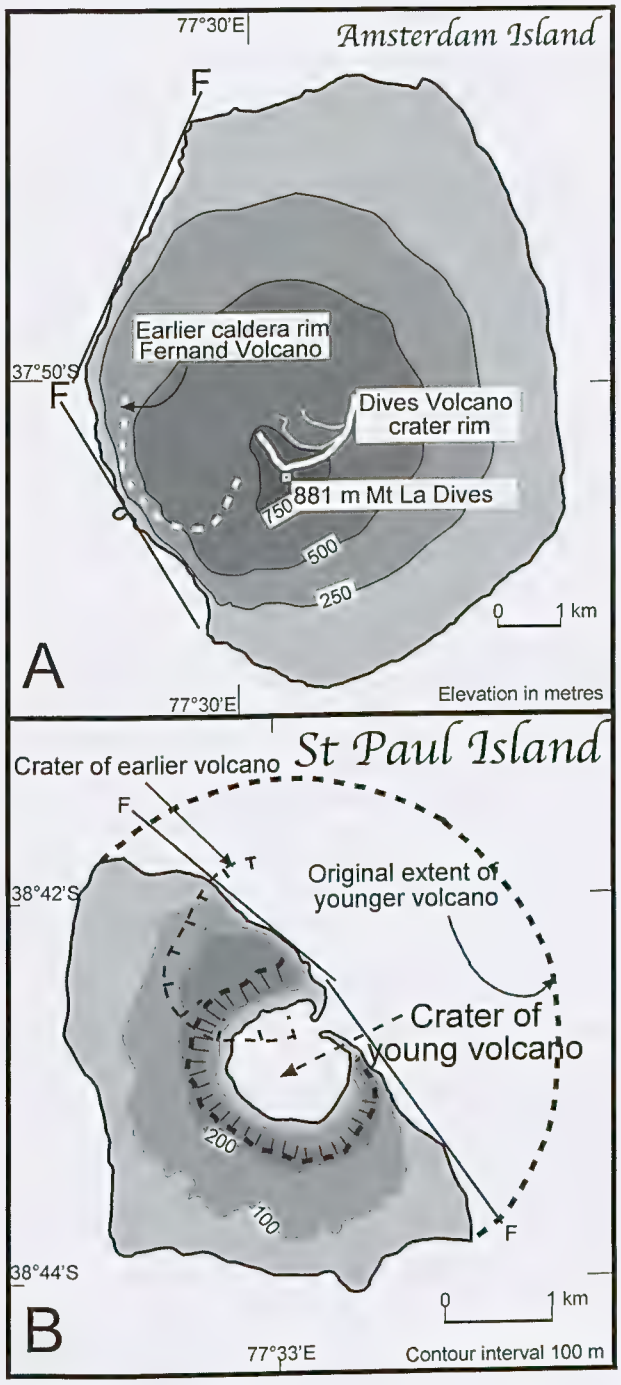


FIG. 19 — Amsterdam and St Paul islands. (A) Amsterdam Island; (B) St Paul Island. F = fault.

The avifauna suffered badly during human occupation and the story of decline and extinction, including one of the endemic species (*Anas marecula* Olson & Jouventin, 1996) is provided by Worthy & Juventin (1999).

St Paul Island has a faulted northeastern margin, along which faulting has removed an estimated 3 km² of the island's original area. It has a central circular crater about 1 km wide and 300 m deep, now up to 80 m below sea level and open to the sea via a shallow gap. The original volcano is visible in the northeastern cliffs but the rest of the island is the result of a younger volcano. Products of the earlier volcano consist of yellowish pumice deposits, originally basalt, which are cut by rhyolite dykes but these rocks are highly altered by weathering. The rhyolitic dykes contain some quartz and sanidine and are described as alkaline rhyolites. The newer volcano consists of basalt flows and fragmental material, but lacking pillow lavas that would indicate submarine eruption. Lavas are diverse basalts. Volcanism is younger than 100 ka and the island still retains hot springs and fumarolic activity.

Overall, the islands are of tholeiitic basalt but there is a difference in lava composition between the two islands with St Paul having lavas with about 51.5% SiO_2, 4% Na_2O and 1.02% K_2O, in contrast with those from Amsterdam Island with 49% SiO_2, 2.5% Na_2O and 0.6-0.7% K_2O. The Na and K are lower in the Amsterdam Island lavas but the ratio between them is the same.

Recently, the 1100-m-high, volcanically active, Boomerang Seamount (37°43.3'S; 77°49.5'E) was discovered on the Amsterdam-St Paul Plateau, 18 km northeast of Amsterdam Island at the intersection of a transform fault and spreading ridge. It has similar lava composition to that of St Paul volcanics (Johnson *et al.* 2000).

Îles Kerguelen

Îles Kerguelen (fig. 20) have, in common with Heard Island, a multi-phase history including a relatively long and dominantly volcanic story interspersed with intervals of sediment formation with peat and fossil leaves and wood and some marine incursions. The area is almost a sub-continent in diversity, composition and complexity (Giret & Lameyre 1983, Nougier & Thomson 1990b). Because of this long history and diverse rock assemblage, the islands may provide information relevant to understanding the evolution of Large Igneous Provinces (LIP) such as Kerguelen Plateau (probably the second largest submarine plateau) which appear to occur only in Cretaceous and younger times.

Îles Kerguelen is complex with a main island (Grande-Terre) some 6500 km² in area and 300–400 other small islands and rocks. The basement of the island can be divided into two major provinces — a northern province (Transitional Tholeiite, fig. 20), and a southern, generally younger province (Alkali Basalt) which may overlie a continuation at depth of the Transitional Tholeiite. The provinces are separated on the surface by a northwest-southeast arcuate boundary. The Transitional Tholeiitic province is composed of flat-lying plateau basalt lavas generated by four shield volcanoes (1–4, fig. 20) centred on an arc parallel to the arcuate boundary. These have ages mainly in the range 38–23 Ma with a few younger dates. The complexes are both plutonic and their volcanic equivalents. There is no evidence, as yet, of a basement with superposed volcanics; plutonic and volcanic rocks are of essentially the same age ranges. The plutonic

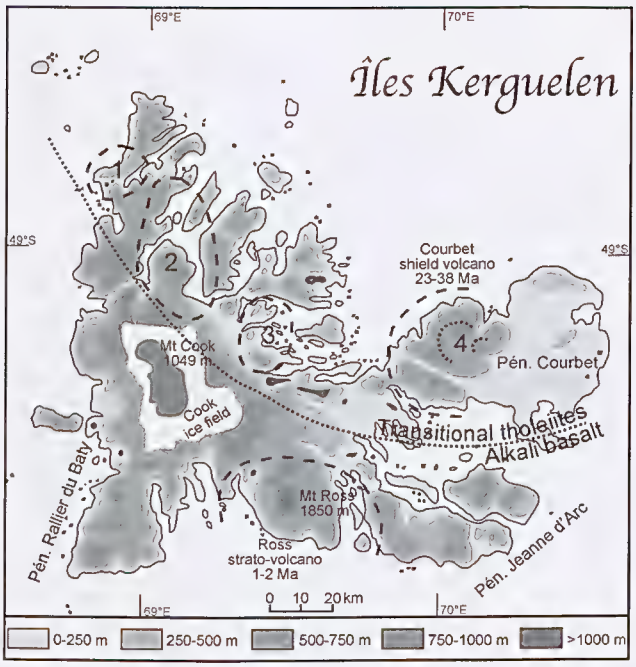


FIG. 20 — Îles Kerguelen. 1–4 in dashed circle = older shield volcanoes of tholeiitic province.

phases, concentrated on western Péninsule Courbet, at Péninsule Rallier du Baty and north of the Cook Icefield include alkali-granite, nepheline syenite and biotite gabbro to emphasise the sub-continental aspect. Ages obtained from the plutonic rocks are older than those from the intruded volcanics and it may be that emplacement of the plutons has reset the original ages of the volcanics (Nougier & Thomson 1990b). The Alkali Basalt province is younger, generally 23–17 Ma, and the ages of the volcanics are consistent with those of the associated plutonics. The basalts have a total thickness of some 1000 m with individual flows 3–10 m thick and interbedded with pyroclastics, rare marine horizons (Fletcher 1938, Fleming 1957), and non-marine members with lignite and silicified tree trunks (Cookson 1947). Volcanism seems not to have been continuous but episodic with products separated by angular unconformities, breccias and sedimentary horizons.

The basement complexes have been intruded by a large number of dykes with strong northwest-southeast and northeast-southwest orientations over the northwestern part of the island, but as concentric ring-dykes around Mt Ross in the central south.

A major plutonic complex was intruded into Péninsule Rallier du Baty at 9–5 Ma and includes quartz-rich syenite and granite, rocks much higher in silica than found in most oceanic islands. It appears to have escaped intrusion by large numbers of dykes that cut the basement.

The major young volcano in the central southern part of the island is Mt Ross — a pyroclastic stratovolcano 15 km in diameter with summit caldera 5 km wide and numerous parasitic cones less than 1 Ma suggesting that they were the end stage of eruption. Mt Ross dates are 2 Ma and younger. To the west of Mt Ross lies Péninsule Rallier du Baty where hot springs and fumaroles are active. Ages of plutonic rocks are 9–5 Ma and there is evidence of Holocene trachyte flows.

Uniquely among oceanic islands, Îles Kerguelen has provided xenoliths of granulite from several localities on Péninsule Courbet and Péninsule Jeanne d'Arc. These

granulites, high metamorphic grade, normally indicative of lower continental crust, include sapphirine. Estimates of the P/T regime are discussed by Gregoire *et al.* (1994) who suggest a temperature of about 900°C and pressure equivalent to that at about 35 km. This gives some indication of conditions that may exist beneath these large submarine plateaux.

The highest part of the island is generally to the west where the Cook Icefield — a remnant of a once much larger icecap — sits on Le Dome (1049 m) but Mt Ross at the south is the highest peak at 1850 m and several peaks are close to 1000 m. The eastern part of the island is generally of lower relief and was the recipient of sediments deposited by river and glacial action. Péninsule Courbet is composed largely of glacial outwash and moraine. Glacial striations are common where the lithology is appropriate.

The complex of islands is a highly radially-glacially-dissected landscape forming a highly indented coast with abundant peninsulas and fjords. An icecap of 600 km² still exists on Le Dome (1049 m) on the central western part of the island.

Heard Island and the McDonald Islands

Heard Island (Barling 1994, Quilty & Wheller 2000, Green & Woehler 2006, Stephenson *et al.* 2006) has a more complex history than oceanic islands in general. The island (fig. 21A) consists of two separate parts — the island proper dominated by the volcano Big Ben (2745 m), and Laurens Peninsula to the northwest with Mt Dixon at its centre. The island is south of the Antarctic polar Frontal Zone and, together with its height, ensures it is heavily glaciated. Three major, and several minor, phases can be recognised in its history over the last 45 Ma. When Central Kerguelen Plateau sank below sea-level at approximately 100 Ma (Wise *et al.* 1992, Quilty 2006), it began to accumulate pale pelagic sediments — nanno/foram ooze — mainly formed of the skeletons of two groups of calcareous planktonic organisms — coccoliths and foraminifera (Quilty *et al.* 1983). The sediments also contain dark horizons probably representing intervals of volcanic activity. These sediments solidified to form limestone inferred to be the basement of the island even if exposed only on the western region of the island. These sediments have been severely disrupted by faulting and tilting between fault blocks but the age of the faulting is not known. Little is known of what happened for a long time but volcanism was active somewhere in the region through much of the interval. Dolerite intrusions form sills in the older limestone and all has been intruded by trachyte dykes. This sequence was then subject to erosion to form a widespread unconformity. At about 9 million years (Truswell *et al.* 2005), a mass of volcanic rocks — the Drygalski Formation to about 350 m thick — accumulated on this unconformity, but the parent volcano was not on Heard Island. The Drygalski Formation contains a mixture of pillow lavas, tuffaceous sediments and marine siltstone but has not been subjected to serious study. It contains a few marine molluscs — particularly the bivalve *Austrochlamys heardensis* (Fleming, 1957) (Quilty *et al.* 2004) which also is known to the east of the island. The land at the time was host to at least two terrestrial vegetation types — open heath with grasses and fern/lycopod/angiosperm but lacking trees. The Drygalski Formation was laid down on the older limestone and in turn formed the foundation for the modern volcanoes of Big Ben and Mt Dixon on Laurens Peninsula.

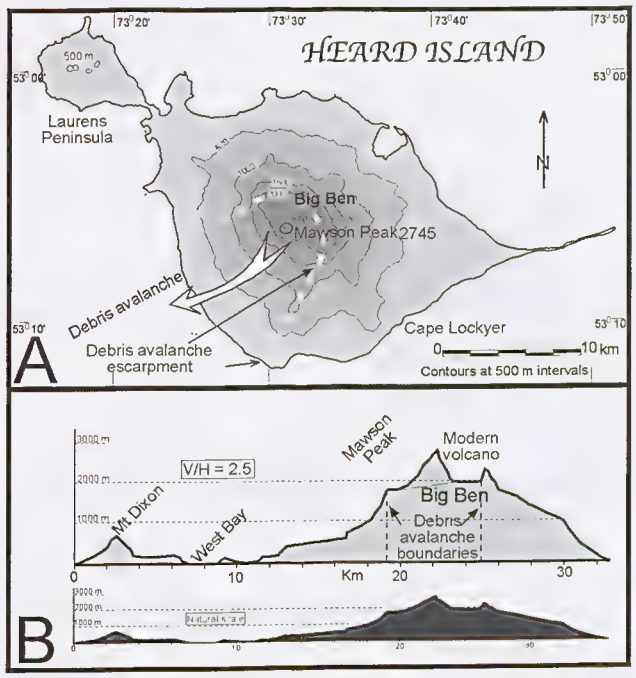


FIG. 21 — Heard Island. (A) Topography and volcanic features. (B) Profile through island at both natural and exaggerated scales.

Big Ben defines the shape of the island and is currently mildly active through the small volcano of Mawson Peak. The age of Big Ben is unknown but likely to be 1 million years or less. Surrounding Big Ben on the coastal fringes of the island are several small cinder cones. The main lavas of Big Ben are highly porphyritic basanites, alkali basalts and trachybasalts with abundant phenocrysts of olivine and clinopyroxene with high titanium content. Ash content of the complex is low except at the smaller marginal cones. Mt Dixon is much younger and an age of about 10 ka has been obtained from lavas under the volcano. It is trachytic with low phenocryst content. It may be only dormant. The island lavas are similar to other oceanic island lavas common in the Indian Ocean probably resulting from deep-seated plumes or hot-spots. Big Ben and Laurens Peninsula lavas are distinct but emanate from a common parent source probably by differentiation of the Big Ben lavas from the primary source which is represented at Laurens Peninsula.

The flanks of Big Ben are marked by steep, radial glaciers flowing between raised rock barriers or buttresses that are prominent features of the island. The eastern end of the island is an elongate spit due to oceanographic distribution of debris from the volcano and from that deposited by the melting of the terminations of the glaciers. Passage of the detrital material around the island provides a basis for shorter longshore drift deposits that enclose several lakes near the edges of the island.

At some stage, the southwestern side of the island has collapsed into the ocean, leaving a major scar (fig. 21B) and a debris avalanche amphitheatre in which the currently mildly active Mawson Peak grew.

Approximately 40 km to the west of Heard Island lies McDonald Island (fig. 22A). The McDonald Island lavas differ from those of Heard Island, being phonolitic with high $Na_2O+ K_2O$ (about 15.5–16.5%).

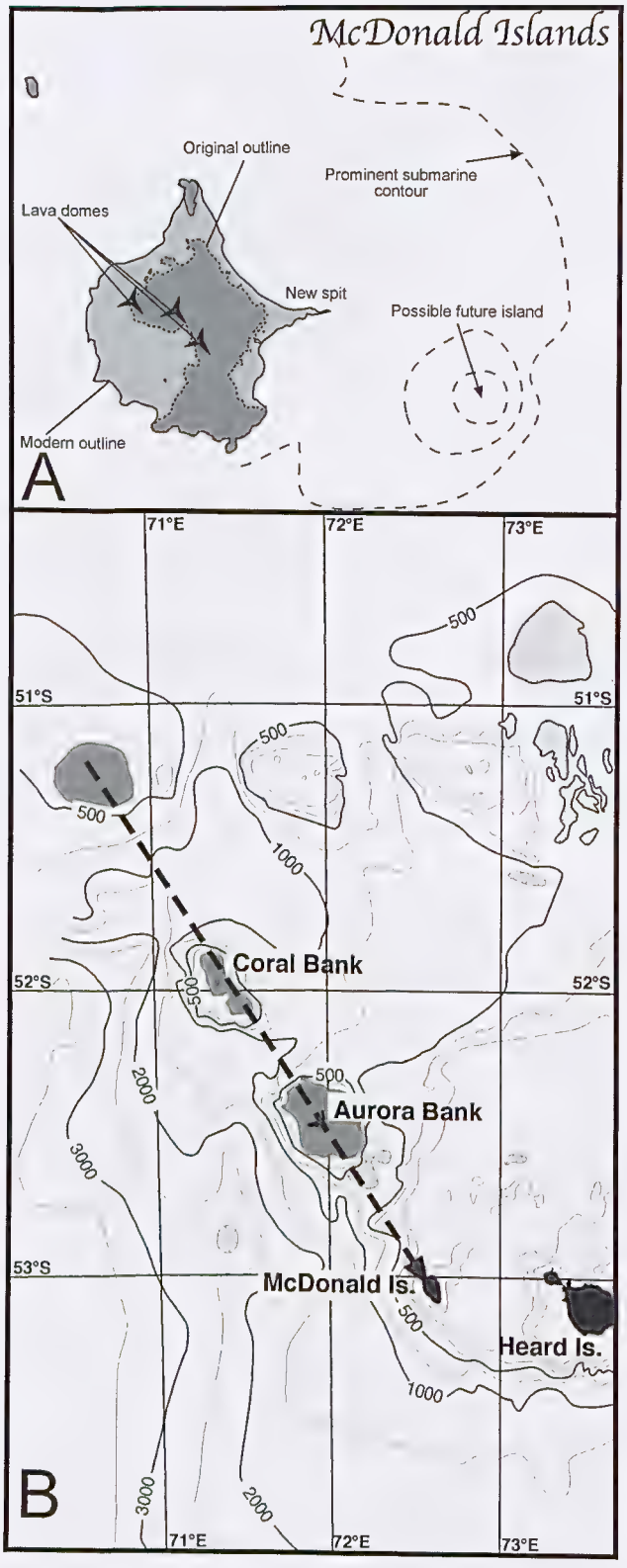


FIG. 22 — Features of McDonald Island. (A) Changes in outline consequent on 1992 and successive eruptions. (B) Possible track of mobile hot-spot leading to McDonald Island.

After a period of quiescence for 75–100 000 years, it was re-activated in December 1992 (Quilty 1995). Several broad lava domes with short radial flows are visible. This activity has continued and changed the face of the island, generating a spit (mimicking that of Heard Island) on the eastern side, and beaches, now inhabited by abundant penguin and seal populations. To the east of the island, several submarine features are visible. There is a large circular submarine contour, probably marking a constant depth of the volcanic construction. To the southeast of the island on this feature, there is a very shallow area commonly with a small cloud over it. It is possible that submarine eruption occurs here and that a new island will emerge above sea level in the near future. McDonald Island raises other questions, especially as they relate to the mobility of volcanic 'hot-spots' (fig. 22B). McDonald Island appears to be stationary at the southeastern extremity of a hot-spot chain which has formed successively three seamounts to the northwest — including Coral and Aurora Banks suggesting that, if all are due to hot-spot activity, the hot-spot is migrating.

CONCLUSIONS

The islands of the sub-Antarctic differ in origin from those most commonly illustrated in popular literature and can be classified into groups of similar origin (table 2).

It has not been possible to treat the geology of all islands to a common depth because all have not been studied to the same extent. Much remains to be done.

Many of the islands are very young, commonly < 1 Ma. It is unlikely that the spectrum of ages is any more unusual now that at any time in the past 10 Ma. In turn it is highly likely that, at any time in the past 10 Ma, a collection of islands with the same range of ages would exist. It thus is probable that the islands, other than those of continental material or on major submarine plateaux, have a very short life span, probably of the order of 1–2 m.y. While the islands may be ephemeral, the larger scale features of which they are the exposed portion, have a longer life as seamounts or guyots.

Despite their diverse origins described above, the sub-Antarctic islands can be grouped into categories with similar origins and histories. With the exception of Macquarie Island, the volcanic islands grew from normal sea floor or ocean plateau depths, are briefly above sea level and most will, in time, sink below sea level. The islands and their categories are summarised in figure 23.

Those involving continental crust. Many of the islands and islands groups are either of continental rock (South Georgia), the result of collision between continental margins and oceanic crust (Diego Ramirez), or sit on submerged thinned continental crust (the islands of the Campbell Plateau — Antipodes, Auckland and Campbell islands). In each of these cases, the islands are close to a continental margin.

Those associated with a subduction zone. This category includes only the 10 islands of the South Sandwich Islands group. These islands have much in common with those associated with subduction zones elsewhere.

Those related to transform faults. The most prominent of these in the sub-Antarctic are Gough Island and the Balleny Islands where the island is part of a linear series, whether or not others of the series are emergent or have sunk below sea level. Peter I Island may belong here.

Those on submarine plateaux. This group is dominantly in the Indian Ocean and includes Îles Kerguelen, Heard and McDonald islands, the Crozet Archipelago and Amsterdam Island and the Prince Edward Islands. There is current debate on the role of thinned, submerged continental crust (cf. Campbell Plateau) as forming the basement to a volcanic veneer on such plateaux. Another view is that the submarine plateaux formed as a thick volcanic pile in the oceanic

TABLE 2
Classification of sub-Antarctic islands

Island	Setting	Age (Ma)
Amsterdam/St Paul	Submarine plateau	<0.45
Antipodes Island	Submerged continental plateau	< 0.5
Auckland Island	Submerged continental plateau	Continental/mid Te
Balleny Islands	Transform fault	<2?
Bouvetøya	Triple junction	0.5
Campbell Island	Submerged continental plateau	K–0
Îles Crozet (Possession)	Submarine plateau	9–0
Diego Ramirez	Continental – collision	Continental
Gough Island	Transform fault	<1 Ma
Heard & McDonald Is.	Submarine plateau	40, 9, 1–0:Active
Îles Kerguelen	Submarine Plateau	39–25; 23–17
Macquarie Island	Raised sea floor	9
Marion & Pr. Edward Is.	Submarine plateau	0.45–Recent
Peter I Island	Transform fault, single	<0.33–0.11
Scott Island	Single, 'simple'/transform	"very young"
South Georgia	Continental crust	Continental
South Sandwich Is.	Subduction related	3–0: Active

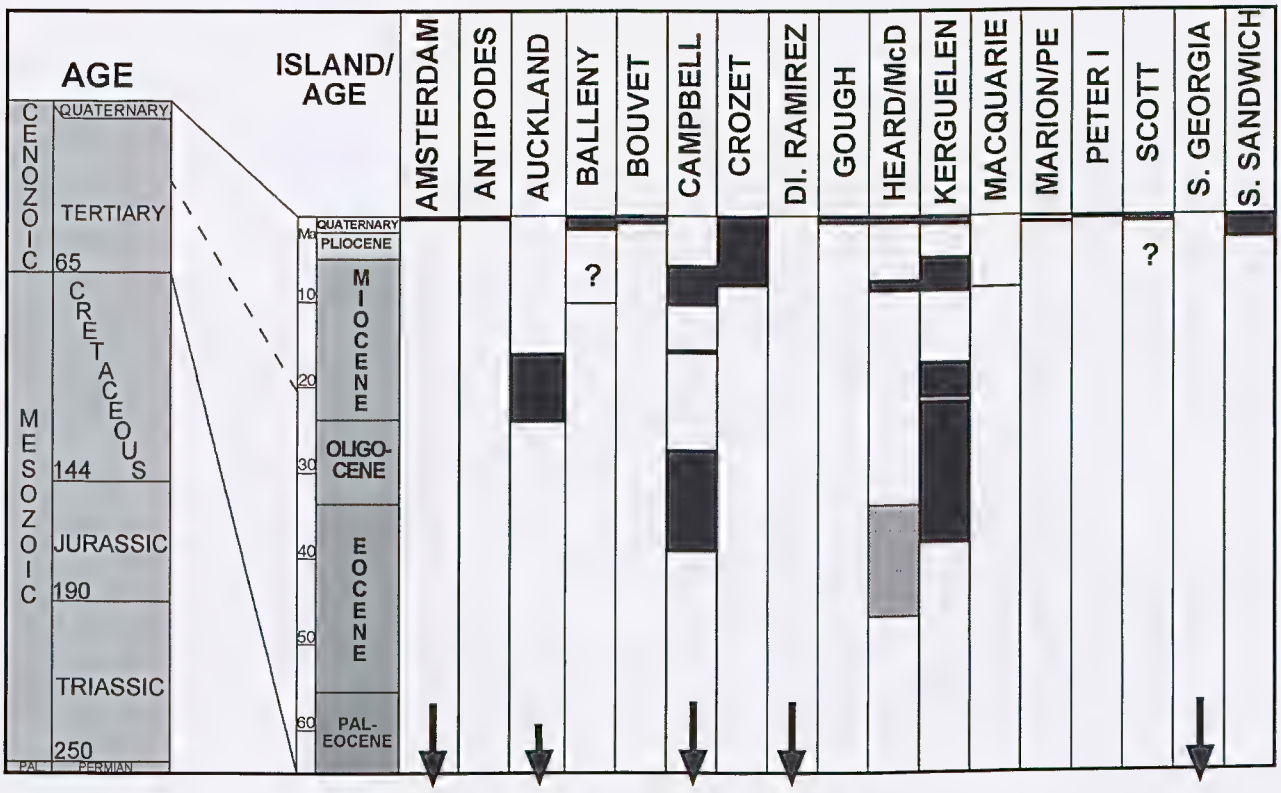


FIG. 23 — Summary of the ages of sub-Antarctic islands.

environment, far from any continent and evolved through several stages over many tens of millions of years. The islands themselves are volcanic and are currently or recently active.

Raised sea-floor. Macquarie Island is unique among the islands discussed in that it formed at a mid-ocean ridge and sank into deeper waters. Because of tectonic activity, it now is situated at the boundary between the Pacific and Indian-Australian tectonic plates, and tectonic interaction between the plates has brought to the ocean surface a piece of the ocean floor. On all other islands described here, the rocks and their structural and mineralogical characteristics formed above sea level i.e., on an emergent island — but on Macquarie Island they formed on the sea floor. Macquarie Island is also different in that it is still rising in contrast to others that are subsiding.

'Simple', single-phase islands. These seem to stand alone and formed in a single episode of volcanic eruption. This group includes Scott Island and Peter I Island, each of which has a small plateau beneath it, and could also be classified as a submarine plateau island. Scott Island could also be assigned to a transform fault association such as for Balleny Islands.

Triple junction. Bouvetøya is not easy to classify into a broader category. It sits close to a triple junction that has been interpreted as marking a long-term hot-spot site. It is not at the triple junction at present and may be an island, similar to Iceland, which formed on a mid-ocean ridge.

ACKNOWLEDGEMENTS

I dedicate this work to the memory of the late Professor Ric Varne, of the School of Earth Sciences at the University of Tasmania, who stimulated my interest in Macquarie Island and who led a group of three to Macquarie Island in 1968. He recognised its global geological significance, reflected in its inscription on the World Heritage List in 1997 — an effort with which he was heavily involved. Varne Plateau on Macquarie Island has recently been named in his honour. I thank the organisers of the meeting held in 2006 to examine the sub-Antarctic, especially Sir Guy Green who was the originator of the idea. I am very grateful to Professors David Green and John Veevers whose reviews improved the final product. Many others have helped me in compiling this summary. I thank them all.

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THE INFLUENCE OF THE ANTARCTIC CIRCUMPOLAR CURRENT ON THE OCEANOGRAPHIC SETTING OF A SUB-ANTARCTIC ISLAND

by Isabelle J. Ansorge and J. R. E. Lutjeharms

(with five text-figures)

Ansorge, I.J. & Lutjeharms, J.R.E. 2007 (23:xi): The influence of the Antarctic Circumpolar Current on the oceanographic setting of a sub-Antarctic island. *Papers and Proceedings of the Royal Society of Tasmania* 141(1): 59–66. ISSN 0080-4703. Department of Oceanography, University of Cape Town, Rondebosch 7701, South Africa (IJA*, JREL). *Author for correspondence.

The circulation in the Southern Ocean is dominated by the Antarctic Circumpolar Current (ACC), which is the only current that flows completely around the globe. The ACC is a complex system consisting of narrow regions of sharp horizontal density gradients, which extend through the entire water column as frontal bands separated by broad zones with less intense gradients. Meridional excursions from the otherwise zonal flow in the form of meanders or mesoscale eddies occur in regions of prominent bathymetric features, suggesting a close relationship between the level of mesoscale sea surface variability and bottom topography. The Prince Edward Islands (Marion Island and Prince Edward Island) lying within the Polar Frontal Zone (PFZ) at approximately 38 °E, 47 °S form a very special terrestrial habitat and have, for this reason, been designated a declared nature reserve. The ecology of the islands is directly dependent on its ocean environment. With the advent of satellite altimetry it has become apparent that the Prince Edward Islands are located on the northern border of a region of remarkably high mesoscale variability. The source of this variability lies where the current jet associated with the ACC intersects the South-West Indian Ridge. From here newly generated eddies are steered by the bottom topography past the Prince Edward Islands. This discovery probably explains the high physical and biological variability found at the islands, and warrants further analysis.
Key Words: Prince Edward Islands, Antarctic Circumpolar Current, meanders, mesoscale eddies.

INTRODUCTION

The Southern Ocean is the oceanic region that surrounds the entire Antarctic continent, and consists of the southern extents of the Atlantic, Indian and Pacific oceans (fig. 1). The Antarctic continent forms its southern boundary, and while the northern border is not physiographically fixed, it is usually considered to coincide with the location of the Subtropical Convergence (Lutjeharms 1985). The unique geography of the Southern Ocean makes it the only place where ocean currents run completely around the globe. Dominating the region is the strong, deep, eastward-flowing Antarctic Circumpolar Current (ACC) — often referred to as the "West Wind Drift" after the strong westerly winds that prevail between 40°S and 60°S sandwiched between the subtropical high pressure belt in the north and the Antarctic trough, which lies south of 65°S (Taylor *et al.* 1978).

The Southern Ocean plays a major role in global ocean circulation and, in particular, on present-day climate. Extending unbroken around Antarctica, the ACC, is by far the largest conduit by which water, heat and salt are transferred between different ocean basins (fig. 1). As these exchanges play an important role in regulating mean global climate, a better understanding of the physical and dynamic processes, which are responsible for the variability of the ACC, is highly important (Budillon & Rintoul 2003). The surface flow of the ACC is driven primarily by the frictional stress of the westerly wind. Combined with the Coriolis force, a northward component to the surface current is responsible for the formation of frontal bands, which act as boundaries separating zones of uniform water mass. These fronts are a distinct permanent feature in the Southern Ocean. They are circumpolar but show a strong temporal and spatial variability in different oceanic sectors (Lutjeharms 1985). Their positions are mainly determined by topographic steering of the ACC (Gordon *et al.* 1978) in combination with the global spatial pattern of wind fields, in particular the distribution of the wind stress curl (Nowlin & Clifford 1982). Transects across the ACC show this current to consist of zones of several quasi-uniform water masses separated by fronts in which horizontal gradients of properties are relatively large. These broad

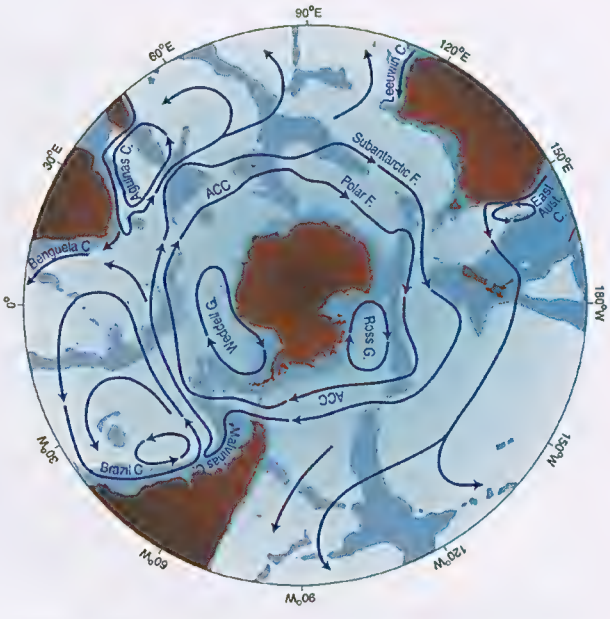

FIG. 1 — Schematic map of the major currents in the Southern Hemisphere south of 20°S. Depths shallower than 3500 m are shaded. The two main cores of the Antarctic Circumpolar Current are shown — the Sub-Antarctic Front (SAF) and the Antarctic Polar Front (APF). The interbasin exchange between the Southern, Pacific, Atlantic and Indian oceans is clearly shown (after Rintoul et al. *2001).*

zones are (from north to south) the Sub-Antarctic Zone, Polar Frontal Zone, Antarctic Zone and the Continental Zone (Whitworth 1980). They are demarcated by the major circumpolar fronts of the ACC; respectively the Subtropical Convergence, Sub-Antarctic Front, Antarctic Polar Front and the Southern Antarctic Circumpolar Front (Lutjeharms & Valentine 1984, Whitworth & Nowlin 1987).

SUBTROPICAL CONVERGENCE

The Subtropical Convergence (STC) marks the boundary between warm, salty subtropical surface water to the north and cooler, fresher sub-Antarctic Surface Water to the south (fig. 2). It is the most prominent surface thermal front with surface temperatures ranging from 10.3–16.9°C (Belkin & Gordon 1996). Its mean position lies at 41°40'S (Lutjeharms 1985). In the western part of the Indian sector it is one of the strongest fronts in the world ocean (Lutjeharms 1985). In this region, the extension of the Agulhas Current, the Agulhas Return Current (Lutjeharms & Ansorge 2001), strengthens the horizontal gradients of this front considerably leading to the formation of intense mesoscale eddies. These heat anomalies have been shown to have a marked influence on the overlying atmosphere and on local biota (Llido *et al.* 2005). Recent investigations at the STC, using both satellite remote sensing as well as modelling (Llido *et al.* 2005), have demonstrated the climatological importance here of primary production. It has been shown that primary production at this front occurs as event-scale blooms and not as persistent enhancement as was suggested previously (Weeks & Shillington 1996).

SUB-ANTARCTIC FRONT

The sub-Antarctic Front (SAF) represents the northern boundary of the Polar Frontal Zone (PFZ) and marks the southern extent of sub-Antarctic Surface Water. In comparison to the STC, which is clearly characterised by a sharp and consistent gradient in both surface and subsurface expressions, making identification extremely easy (Lutjeharms & Valentine 1984), the SAF is less clear in its surface expression. The exact boundaries of the PFZ can therefore be difficult to identify due to the weak nature of this front. The SAF is predominantly a subsurface front and can be defined by the most vertically orientated isotherm within a temperature gradient lying between 3°C and 5°C, while its surface expression extends between 8°C and 4°C. As the surface expression is generally weak, the subsurface structure with the 6°C isotherm as its core is usually the preferred indicator. Despite its ill-defined surface expression, recent investigations (Swart *et al.* ms) have found that the SAF contributes over 30% to the volume flux of the ACC. The subsurface SAF axial indices remain fairly stable lying at a mean location of 47°25'S (Lutjeharms & Valentine 1984, fig. 2).

ANTARCTIC POLAR FRONT

The Antarctic Polar Front (APF) or Antarctic Convergence marks the northern limit of the Antarctic Zone where Antarctic Surface Water moving northwards sinks below warmer sub-Antarctic water masses. The APF is a region of elevated current speeds and strong horizontal gradients in density, temperature and salinity (Deacon 1937, 1983). The

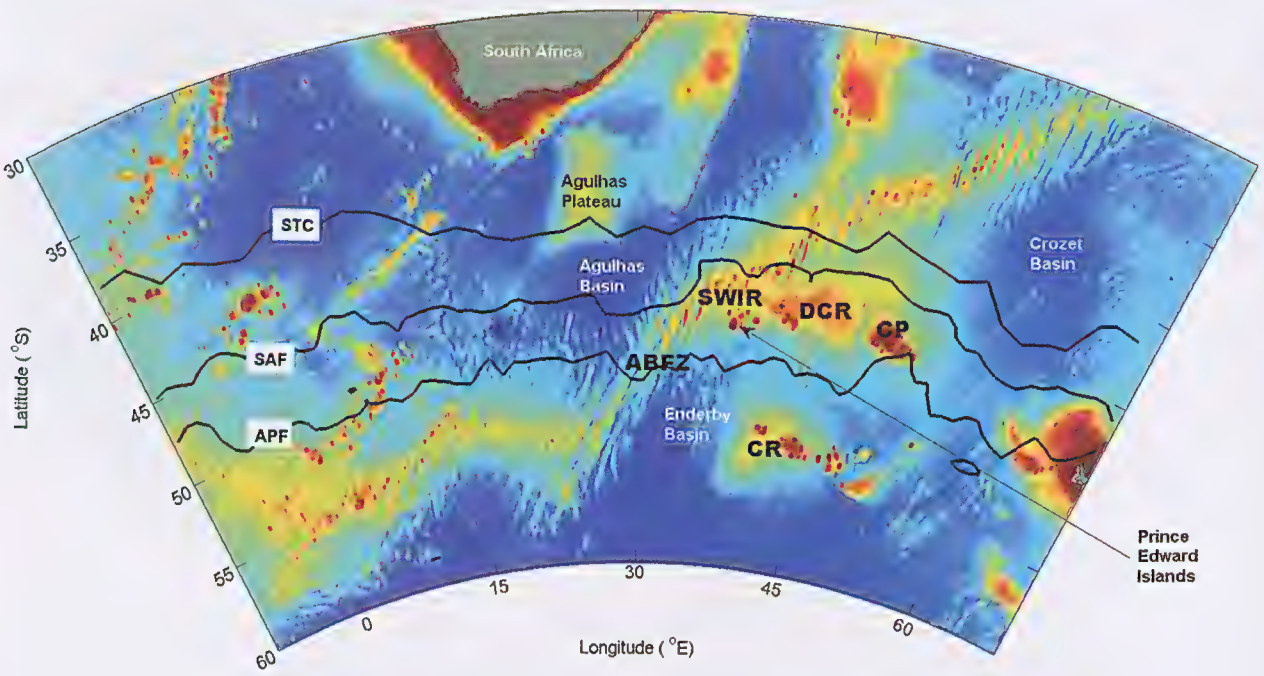

FIG. 2 — Schematic showing the locations of the subsurface expressions of the Sub-Antarctic, Antarctic Polar Fronts and the Subtropical Convergence in the eastern Atlantic and western Indian Ocean sectors of the Southern Ocean. SWIR denotes the South-West Indian Ridge, ABFZ = Andrew Bain Fracture Zone, DCR = Del Cano Rise, CP = Crozet Plateau and CR = Conrad Rise. The location of the Prince Edward Islands is clearly shown.

subsurface expression of the APF historically is identified by the northern limit of the 2°C temperature minimum at a depth of 200 m (Whitworth 1980). However, the surface and subsurface expressions do not always coincide and are often approximately 50 km apart (Lutjeharms & Valentine 1984). In these instances the surface expression can be identified by the maximum temperature gradient between 6°C and 2°C. The APF can be further characterised by a shallow temperature minimum associated with the remnants of Winter Water, which lies at depths between 50 and 150 m. It is seasonally variable; in winter it is nearly homogenous extending to 250 m, while in summer the mixed layer extends only to between 50 and 100 m. Surface sea temperatures range from –1.8° to 6°C at the APF. The APF has a mean location of between 52°S and 53°S (Orsi *et al.* 1995, fig. 2).

Current measurements at the Drake Passage have shown the ACC to include an additional frontal feature south of the APF, called the Southern Antarctic Circumpolar Current Front (Orsi *et al.* 1995), corresponding to the position of the atmospheric low-pressure belt known as the Antarctic trough (Taylor *et al.* 1978).

In this paper we present an overview of the ocean variability in the Southern Ocean, in particular the influence prominent bathymetry may have on ocean circulation. Using the sub-Antarctic Prince Edward Islands as a case study, we highlight how changes in the flow of the ACC brought on by topographical steering and eddy generation have a marked effect on the ocean environment of these islands as well as on the local distribution of biota (Bernard *et al.* 2007)

VARIABILITY IN THE SOUTHERN OCEAN

Extensive investigations have been carried out in the past decades to understand the flow pattern of the ACC and the extent of its temporal and spatial variability throughout the Southern Ocean. A good correspondence between the increased surface speeds of the ACC and the locations of the three main fronts — the STC, SAF and APF — seems to exist (Hofmann 1985). A banded current structure clearly occurs within the ACC. Meridional excursions from the otherwise zonal flow in the form of meanders or mesoscale eddies occur in regions of prominent bathymetric features, suggesting a close relationship between the degree of mesoscale sea surface variability and bottom topography (fig. 3). Indeed, global charts of sea surface height anomalies in the world's oceans (Nerem *et al.* 1994) show certain persistent patterns in the Southern Ocean, with regions of high mesoscale variability correlating closely where the ACC interacts with prominent bottom topography such as the South-West Indian Ridge, Crozet and Kerguelen Plateaux and the Macquarie Ridge or at choke points such as the Drake Passage (fig. 3). The importance these regional "eddy hotspots" have in influencing exchange between the Southern Ocean and adjacent ocean basins is currently the focus of many projects. This interbasin exchange provides an important link in the meridional heat and salt fluxes that balance much of the ocean-atmosphere exchange. It has been suggested by de Szoeke & Levine (1981) that the meridional heat flux required to balance the heat lost through air-sea exchange in the Southern Ocean may be accomplished by the cross-frontal advection of mesoscale eddies. Indeed, direct measurements of regions of high variability near the Drake Passage (Johnson & Bryden 1989), South-West Indian Ridge (Ansorge *et al.* 2006) south of Tasmania (Phillips & Rintoul 2000) and south of New Zealand (Bryden & Heath 1985), as well as numerical model estimates (Jayne & Marotzke 2002) show consistent eddy heat fluxes across the ACC with values ranging between 11.3 kWm^{-2} and 15.4 kWm^{-2}. Furthermore, these studies have shown that cold eddies exhibit a negative heat and salt anomaly relative to the ambient waters by transporting cool, low salinity, polar water northwards across the APF into the PFZ, while warm eddies offer the reverse with a positive heat and salt anomaly by their transport of warm, saline water masses southwards. The geographic distribution of such eddies is, however, very inhomogeneous. One such region that stands out as such an "eddy hotspot" is the South-West Indian Ridge centred at 30°E, 50°S (fig. 3).

A CASE STUDY — THE PRINCE EDWARD ISLANDS

Sub-Antarctic islands such as the Prince Edward Islands (Marion Island and Prince Edward Island) are classified as isolated, hostile, impoverished regions, in which the terrestrial and marine ecosystems are relatively simple and extremely sensitive to perturbations. They provide an ideal ecological laboratory for studying how organisms, ecological processes and ecosystems respond to a changing climate in the Southern Ocean (Smith 2002). Furthermore, these islands are seasonally characterised by enormous populations of top predators and subsequently any changes in the frontal dynamics, either in the vicinity of these islands or further afield, may have strong implications on their foraging behaviour as already shown from studies on the Grey-headed Albatrosses (*Thalassarche chrysostoma* (Forster,1785)) (Nel *et al.* 2001).

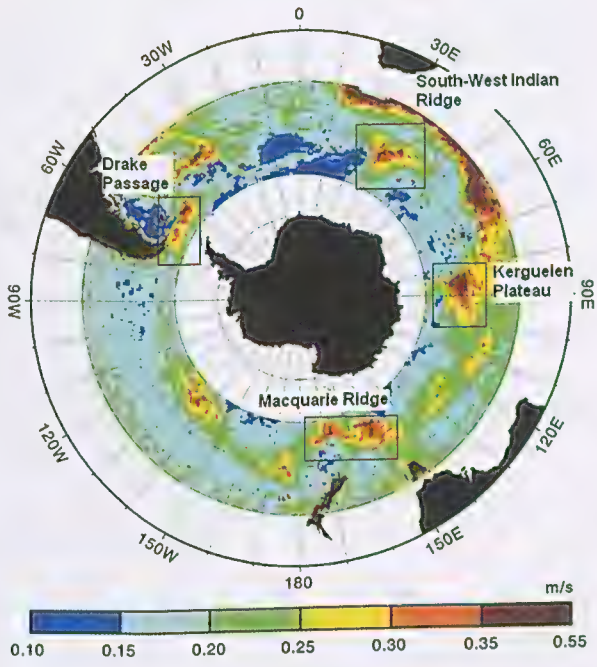

FIG. 3 — Distribution of areas with high levels of Eddy Kinetic Energy in the Southern Ocean (after Gille et al. *2000). The regions of high variability are shown in red. One area of interest can be found at 50°S, 30°E and relates to the high variability associated with the South-West Indian Ridge.*

As a consequence, the Prince Edward Islands can be considered as biodiversity hot spots within the Southern Ocean. The energy necessary to sustain such large numbers of top predators is derived from the close interaction between the oceanic environment and the islands themselves. Changes in the intensity and geographic position within these frontal systems are likely to coincide with dramatic changes in the distribution of species and total productivity within the Southern Ocean.

The South-West Indian Ridge extends from the southwest to the northeast and lies to the immediate west of the Prince Edward Islands. As in the case of all mid-ocean ridges it is criss-crossed by fracture zones (figs 2, 4), such as the Andrew Bain fracture zone at 50°S, 30°E. The Prince Edward Islands lie directly east of the South-West Indian Ridge on a distinct and independent pinnacle that rises from about 5000 m depth. This is particularly clear to the south, whereas to the north it is somewhat complicated by other seamounts that do not break the sea surface. To the northeast lies an extensive shallow feature, the Crozet Plateau. A large part of this zonal rise is shallower than 2000 m. Îles Crozet lie on its easternmost extremity. It is clear that this complex pattern of ridges and rises (fig. 2) forms important restrictions to the flow of the ACC resulting in enhanced variability (fig. 3). Hydrographic data collected during the South-West Indian Ocean Experiment in 1993 and 1995 (Pollard & Read 2001) have shown that close to the South-West Indian Ridge the ACC splits, and further to the east there appears to be a distinct separation in these branches with the SAF deflected northeastwards, thus widening the PFZ by up to 5° of latitude. Modelling results (Craneguy & Park 1999) have also indicated that the position of the SAF and APF, and thus the degree of variability, are dependent on the velocity at which the ACC approaches the South-West Indian Ridge.

Extensive XBT (Expendable Bathythermograph) surveys between South Africa and the Prince Edward islands have shown that these islands (47°S, 37°E) are located within the core of the ACC, sandwiched between the SAF to the north and the APF to the south (fig. 2) (Lutjeharms 1985). These fronts separate sub-Antarctic Surface Water from Antarctic Surface Water, with a zone of transition known as the PFZ between the two (in which sub-Antarctic Surface Water gradually modifies, becoming cooler and fresher to form Antarctic Surface Water). The SAF and APF demonstrate a high degree of latitudinal variability in this region (Lutjeharms & Valentine 1984). Deacon (1987) has postulated that the complexity of the ACC in the vicinity of the Prince Edward Islands results in an increase in the interchange of Antarctic and sub-Antarctic Surface Water within the PFZ here. Furthermore, sea surface temperature data suggest that these islands may be influenced by the intermittent passage of both warm and cold core eddies from further upstream (Ansorge & Lutjeharms 2003, 2005, Ansorge *et al.* 2006).

The clear implication of this behaviour is that the Prince Edward Island region has an enhanced anomaly presence not so much because of the interaction of the flow with the islands themselves, as has been inferred previously (Ansorge *et al.* 1999, Ansorge & Lutjeharms 2003), but as a consequence of the fact that they are situated at the northern border of this region of unusually high mesoscale variability in the Southern Ocean (fig. 3). Indeed, previous investigations have shown that eddies generated at this ridge move northeastwards over a period of 11 months in a narrow corridor between 48–49°S and 34–38°E before dissipating (fig. 4) (Ansorge & Lutjeharms 2003, Ansorge *et al.* 2006). None of these eddies to date have been observed east of 45°E indicating that their anomalous heat and salt content are usually mixed out over this distance. A time-series of sea surface height anomalies within the eddy corridor (48°30'S and 35°E), for 2002–2006, shows that on average five eddies pass through this point per year. A well-studied example of a cold eddy observed in 2005 was illustrated by Ansorge *et al.* (2006, fig. 5) in the lee of the South-West Indian Ridge between 48°–49°15'S and 33°–36°E. Its rotation was cyclonic with speeds exceeding 0.6–1.3 ms^{-1} at the southeast and northwest boundaries and approximately 0.15-0.25 ms^{-1} within its core. The feature exhibited a steep shoaling of isotherms (fig. 5) and

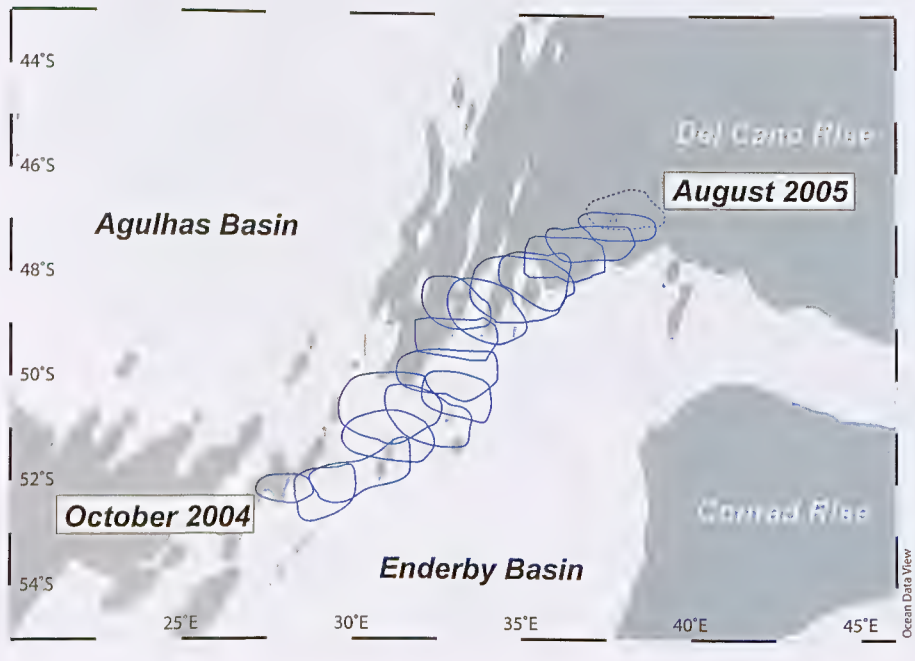

FIG. 4 — The northeastward translation of the cold eddy from the South-West Indian Ridge to the vicinity of the Prince Edward islands at approximately 47°S, 38°E (after Ansorge et al. *2006). Temporal intervals between locations are between 10 and 30 days. The 4000 m isobath highlighting the location of the South-West Indian Ridge in relation to the passage of the cold eddy has been shaded.*

isohalines characteristic of a cold eddy. Typical upper-layer profiles of temperature across the cold eddy show a well-developed subsurface temperature minimum layer (T_{min} = <0.5°C), which is capped in the top 100 m by a relatively warm >4.2°C surface layer (fig. 5). Observations south of Australia (Morrow *et al.* 2004) have shown that cold eddies following detachment from the APF quickly lose their sea surface temperature signature as a result of summer warming of the surface layers. Consequently the subsurface layer provides a better indicator of eddy origin.

A horizontal section through the eddy at a depth of 200 m gives its dimensions and demonstrates the contrast between the temperature of its core waters and that of the surrounding waters. The core of the eddy had temperatures of <1°C whereas the surrounding water was warmer than 3°C and corresponding salinity values between 34.121–34.135 are indicative of Antarctic water masses within its core. The eddy was not entirely circular, but had a mean diameter of about 220 km. This, and satellite altimetry, shows unambiguously that its waters had their origin south of the APF. This is also evident from a vertical hydrographic section through the eddy (fig. 5). The observed temperatures to a depth of 920 m demonstrate the sharp distinction of waters in the eddy and those outside it. This was when the eddy was still fairly young and had not undergone much mixing with its environment.

The temperature minimum at roughly 240 m depth (fig. 5) is characterised by Antarctic Winter Water still intact so shortly after the eddy had formed. The thermohaline structure of Antarctic Winter Water is determined by seasonally changing air–sea interactions such as air–sea fluxes of momentum, heat, freshwater as well as the advection, formation and melting of sea ice (Park *et al.* 1998). In winter it is nearly homogenous extending to 250 m, while in summer the mixed layer extends only between 50 and 100 m. Temperature ranges are large, from –1.8°C to 6°C at the APF, and salinity from 33.4–34.2. The close relationship with changing atmospheric conditions provides a unique imprint on the structure and character of Antarctic Surface Water and thus the random transport of this water mass across the APF by mesoscale eddies must be considered in understanding better regional climatic variability. At the base of the Antarctic Surface Water (AASW) lies Circumpolar Deep Water (CDW) characterised by relatively warm, salty and low-oxygenated waters. The most unambiguous demarcation between the AASW and the CDW is the strong oxygen gradient associated with a rapid decrease in oxygen concentration (Park *et al.* 1998), separating the highly oxygenated AASW (>7 ml l^{-1}) from the oxygen-poor CDW (<4 ml l^{-1}). Furthermore, a vertical salinity section across the eddy clearly shows a distinct shoaling of isohalines. Salinities increased with depth (34.20–34.68) with >34.3 observed below 380 m within the core of the eddy further suggesting the presence of CDW.

The eddy was first observed in satellite altimetry in October 2004 and by August 2005 had sufficiently dissipated that it was no longer observable as a distinct sea surface height anomaly (fig. 4). This lifetime of less than a year is typical

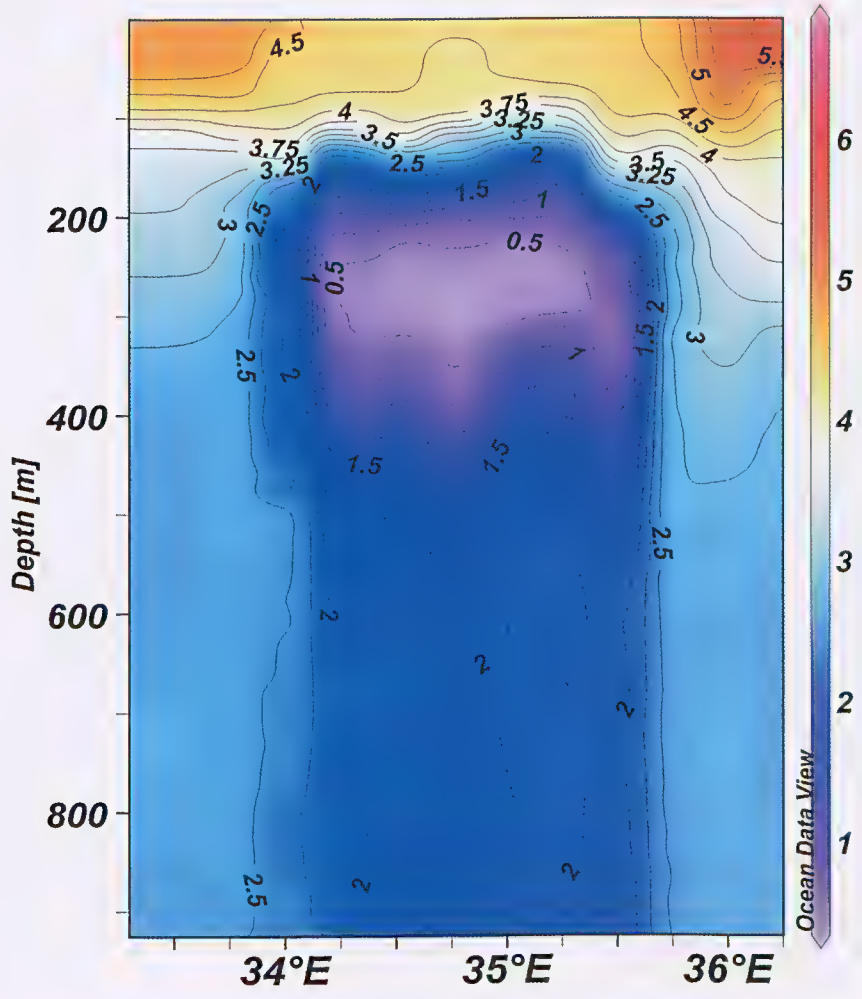

FIG. 5 — Vertical temperature section across a cold core eddy, which was observed in April–May 2005.

for this type of eddy. The introduction and, consequently, dispersal of an insular volume of a pure Antarctic water mass into the PFZ by a cold eddy may play an important role in the meridional biological flux across the ACC (Bernard *et al.* 2007). A regular supply of these eddy types will therefore influence the foraging behaviour of the top predators, resulting in potential important impacts on the ecosystem of the Prince Edward Islands (Nel *et al.* 2001).

The view that the ocean region around the Prince Edward Islands represents a transition *zone* between the warmer sub-Antarctic waters to the north and colder Antarctic Surface Waters to the south is reflected in the euphausiid species composition within the region, with species subtropical, sub-Antarctic and Antarctic in origin co-occurring at any one time (Gurney *et al.* 2002). A number of previous studies (Endo & Wiebe 2005, Mackas *et al.* 2005) have demonstrated that the zooplankton community associated with eddies is distinguishable from the surrounding waters. The euphausiids observed outside the cold eddy in the PFZ waters were typical of this region (Pakhomov & Froneman 2000, Froneman *et al.* 2002, Gurney *et al.* 2002). In contrast, the euphausiids sampled within the core region comprised mainly vagrants (*Euphausia triacantha* and *E. frigida*) that are rarely recorded within the PFZ (Pakhomov & Froneman 2000; Gurney *et al.* 2002), and are typically associated with Antarctic water masses found south of the APF (Mauchline & Fisher 1969). It is possible that the zooplankton found in the core of an eddy reflect the area where the eddy has been spawned. The presence of Antarctic species suggests that the eddy, formed south of the APF, was able to retain and transport the euphausiid species that were distinctive of the front. However, despite the potentially important role the complexity of the PFZ may play in the island ecosystem, few studies have been conducted in the region of the South-West Indian Ridge. Further investigations need to address what implications this unusual eddy street has on the marine ecosystem of the Prince Edward islands.

The PFZ is characterised as a transitional region in which warm, salty sub-Antarctic water masses are gradually modified with distance south. In addition, it has been shown that the PFZ forms a primary sink for the formation of Sub-Antarctic Mode Water (SAMW) and Antarctic Intermediate Water masses (AAIW). Identified as a salinity minimum in the water column, these water masses mark the base of thermocline ventilation into the Southern Hemisphere and form a major source of freshwater input into the world oceans. The consistency with which these water masses are formed and exported is vital in maintaining the freshwater budget and thus the thermohaline overturning of the world's oceans. The introduction of an insular volume of a pure Antarctic water mass into the PFZ by a cold eddy may play an important role in the meridional biological flux across the ACC. Traditionally the northward transport of Antarctic water masses across the ACC has been attributed to Eckman transport; however, the cross-frontal advection of cold eddies from the AAZ into the PFZ may in fact play a central role in altering the physical-chemical characteristic of this region (Sloyan & Rintoul 2001).

Despite the importance of these processes, variations in cross-frontal eddy exchange and their contribution to the formation or modification of SAMW remains one of the most poorly observed quantities in the Southern Ocean and coarse resolution climate models do not accurately resolve the transport associated with these features neither do they resolve the implications these isolated bodies of water have on the local ecosystem. Such changes in the character of the PFZ forced by the introduction of cold, fresh Antarctic water masses could dramatically affect the productivity of this region.

CONCLUSION

The meridional heat fluxes in the Southern Ocean are a key component for the accurate simulation of the global ocean circulation in models and in our ability to understand better interannual and decadal changes occurring in the Southern Ocean. If the assumption is correct that the greater part of this flux comes about through mesoscale eddies, then the quantification of the fluxes at those regions where the mesoscale turbulence is highest (fig. 3) may well be crucial. These eddy fluxes may, however, be very sensitive to changes in the velocity and position of the ACC. Furthermore, subsurface observations have shown an increase of 0.17C° since 1950 in the Southern Ocean, possibly brought on by a southward shift in the position of the ACC (Gille 2002). Consequently, shifts in the position of the main frontal bands associated with the ACC may possibly affect and influence the efficiency with which eddies are generated at eddy pumping regions, such as the South-West Indian Ridge. Recent studies have shown that once formed such eddies advect northeastwards into the vicinity of the Prince Edward Islands (fig. 4) before gradually spinning down within the PFZ (Ansorge & Lutjeharms 2005, Ansorge *et al.* 2006), The precise role of these eddies in the local marine and island ecology needs focused research. It seems possible that the ecosystem of the Prince Edward Islands benefits substantially from its location in the vicinity of the eddy street originating at the South-West Indian Ridge. Indeed, these eddies carry with them organisms from their region of origin suggesting that the surrounding waters of the Prince Edward Islands have a much more diverse spectrum of biota than one would normally expect from an island in the sub-Antarctic (Bernard *et al.* 2007). Moreover, these and other eddies create unusual habitats of their own, particularly at their borders. This has become evident from the feeding behaviour of some birds (Nel *et al.* 2001). The further study of this mechanism and its implications is being planned.

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CLIMATE AND CLIMATE CHANGE IN THE SUB-ANTARCTIC

by S. F. Pendlebury and I. P. Barnes-Keoghan

(with 12 text-figures and one table)

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Meteorologically, the sub-Antarctic is sparsely represented in the climate literature. Drawing on a variety of sources that are either directly or indirectly linked to the sub-Antarctic, an overview of the climate of the sub-Antarctic is presented. In doing so, we note that, for the most part, the sub-Antarctic climate is more or less fixed to mean monthly air temperatures between –5°C and +15°C. Brief discussion explores the roles of teleconnections that appear to affect the sub-Antarctic climate, focusing on the Southern Hemisphere Annular Mode (SAM). We report on meteorological evidence of climate change that has occurred in the recent history of the sub-Antarctic and note that rainfall climate-change signals from Marion and Macquarie islands are consistent with trends associated with the SAM index. We report that modelling suggests that the climate of the sub-Antarctic will continue to change through the twenty-first century in line with twentieth-century trends. The need for more research into the climate of the sub-Antarctic, underpinned by a robust databank of quality controlled sub-Antarctic meteorological data, is noted.

Key Words: climate, climate change, Marion Island, Macquarie Island, Southern Annular Mode, sub-Antarctic, teleconnections.

INTRODUCTION

Despite its importance as part of the global climate system, and the sensitivity of many of its biological systems to climate change, there is remarkably little published information on either climate or climate change in the sub-Antarctic. Much of the limited discussion that is available in the literature appears to represent the sub-Antarctic through reference to the climate at individual locations; figure 1 shows most of the stations and geographical features referred to here. Smith (2002), for example, discussed climate change in the sub-Antarctic using recent changes on Marion Island as an illustration, while Whinam & Copson (2006) used Macquarie Island as their reference point. These two papers also have climate change impacts on biota as the underlying reason for presentation of the work, which may reflect a dearth of purely meteorologically-based discussion on climate and climate change in the sub-Antarctic. Even the largely meteorological paper of Rouault *et al.* (2005) is mostly confined to considering climate changes evident around Marion Island. There is some discussion of Antarctic climate that has some relevance to the sub-Antarctic; for example Turner & Pendlebury (2004) reported on climate and weather forecasting aspects at various stations in the sub-Antarctic though their focus is on the Antarctic itself.

Drawing on a variety of sources that are either directly or indirectly linked to the sub-Antarctic, the current paper seeks to give an overview of the climate and climate change of the sub-Antarctic as a whole. We start by briefly describing the role of ocean currents and the geographical extent of the sub-Antarctic within our purview; we then discuss the broad features of the surface climate of the sub-Antarctic. The paper then provides a brief discussion on a few of the important teleconnections which appear to affect sub-Antarctic climate. Finally, we report on meteorological evidence of climate change that has occurred in the recent history of the sub-Antarctic, and on modelling of that which might occur over the twenty-first century.

OCEANS AND THE SUB-ANTARCTIC

Ocean currents affect climates, arguably none more so than the climate of the sub-Antarctic. Ocean currents are often bordered by marine frontal surfaces (or convergences): narrow regions of relatively rapid transition in water temperature and salinity. Figure 1 shows the main Southern Hemisphere marine fronts, adopting the scheme of Belkin & Gordon (1996). Key features are a Polar Frontal Zone between the sub-Antarctic Front and the more southern Polar Front, and an Antarctic Zone south of the Polar Front. The Subtropical Frontal Zone has, as its northern boundary, the North Subtropical Front and as its southern boundary the South Subtropical Front. These two fronts merge into a single Subtropical Front south of Australia. Another subtropical-type front is the Agulhas Front in the southwest Indian Ocean. North of the Îles Kerguelen area the subtropical, sub-Antarctic and Antarctic Polar fronts become almost indistinguishable. Similarly, the sub-Antarctic and Polar fronts almost blend in the far southwest Atlantic Ocean, while north of the Marion Island–Îles Crozet region the sub-Antarctic Front comes very close to the South Subtropical Front. Elsewhere the sub-Antarctic Front is quite separate from its more northern counterparts.

The Antarctic Circumpolar Current (ACC) flows eastward around Antarctica over the latitude band 40–65°S (King & Turner 1997) associated with the complex structure of fronts outlined above. Fyfe & Saenko (2005, p. 3068) stated that "the ACC profoundly influences, and is influenced by, the regional and global climate". The ACC carries more water than any of Earth's other ocean currents, and 75% of this flow occurs between the Antarctic Polar Front and the sub-Antarctic Front (American Meteorological Society 2000). Following the King & Turner (1997) representation, figure 2 is a sketch of a typical slice of the waters that surround Antarctica south of the South Subtropical Front. The figure gives a sense of the gradients in surface temperature and current velocities. King & Turner (1997) equated the sub-Antarctic Front with the Subtropical Convergence (Subtropical Front): this can be reconciled with the Belkin & Gordon description by assuming the King & Turner

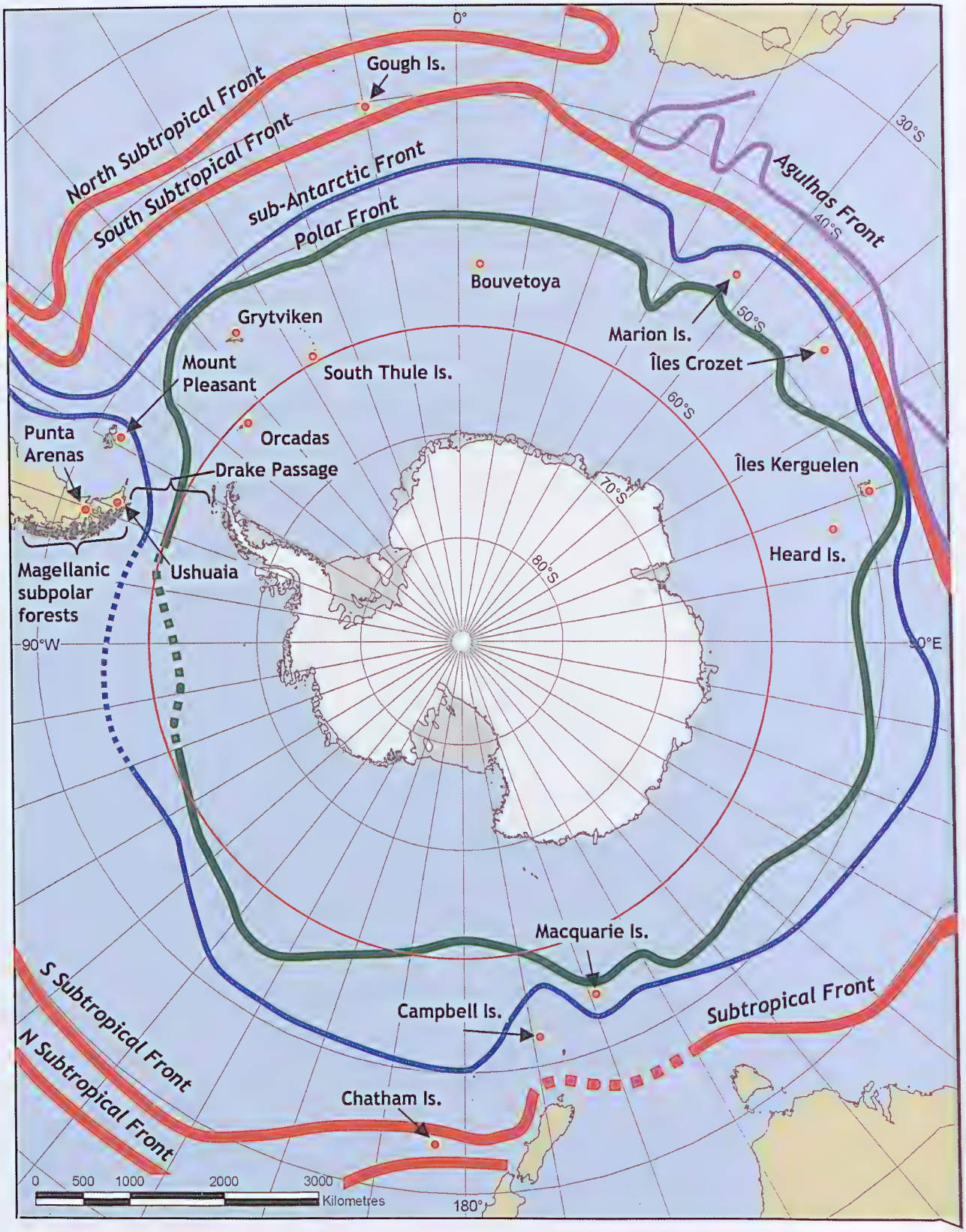

FIG. 1 — Sketch of the locations of key high-latitude oceanic "fronts" and of many of the places referred to in the text. The frontal positions are from Belkin & Gordon (1996). The base map was produced by the Australian Antarctic Data Centre.

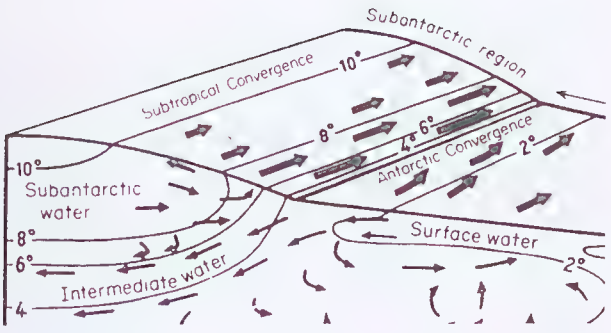

FIG. 2 — Sketch of the locations of key high-latitude oceanic "fronts" and typical winter-time surface isotherms (°C). Adapted from King & Turner (1997).

(1997) Subtropical Convergence is the equivalent of the Belkin & Gordon (1996) South Subtropical Front.

Not only are ocean currents and fronts key components of the climate system; they can be used to delineate the sub-Antarctic. For the purposes of this paper the sub-Antarctic is considered to extend northwards from the northern limit of the Antarctic, which, according to the Antarctic Treaty System, is at 60°S (Antarctic Treaty Secretariat 2007) to include oceanic areas south of the North Subtropical Front, plus adjacent land areas which have monthly mean temperatures less than about +15°C. This comprises a band of about 25° of latitude spanning the southern Atlantic, Indian and Pacific oceans. The landmasses of Africa and Australia constrain the sub-Antarctic to be south of these continents, although the most southern parts of South America are within the sub-Antarctic.

A common criterion for the identification of the South Subtropical Front involves temperatures from the surface to 200 m depth in the order of +10°C (see fig. 2), although some definitions allow the northern edge of the South Subtropical Front surface water temperature to be as high as around +18.5°C over summer (Belkin & Gordon 1996). This criterion makes the above geographical boundaries of the sub-Antarctic consistent with the maritime/taiga land climate of Stern *et al.* (2000). However, while the polar maritime air mass of Stern *et al.* (2000) is characterised by mean monthly temperatures representative of areas south of the tree line, there is a very strong case for the Magellanic subpolar forests (which include, for example, *Nothofagus antarctica* (G.Forster)Oerst.) of far southern Chile and Argentina to be considered as being in the sub-Antarctic. A similar case may be made for the forests on Auckland and Snare islands in the New Zealand sub-Antarctic island-group (United Nations Environment Programme 1998).

THE SURFACE CLIMATE OF THE SUB-ANTARCTIC

Existing studies into the climate of the sub-Antarctic are largely derived from observations at individual land-based stations. An attraction of using meteorological data taken at individual stations to characterise the climate of the sub-Antarctic is that the data would seem to be unambiguous. Strictly, such data apply only to the station itself and only give an approximation to the surrounding land or ocean. Southern South America aside, the land in the sub-Antarctic consists of isolated islands, and with only limited reason for shipping, there are little in the way of "conventional" observations. However, the increasing availability of remotely-sensed observations should gradually allow more detailed analyses of the climate of the entire sub-Antarctic.

As with all climate studies, the homogeneity of data used to describe sub-Antarctic climates must be considered. Changes to instrument type, siting, surrounds or reading practice can have significant effects on the observations even from what appears to be a single, stable station. Conventional homogeneity testing often relies on the existence of data series from neighbouring sites to provide a baseline; as most of the sub-Antarctic stations are remote, such baselines are often difficult to construct. There is no widely available set of meteorological data for sub-Antarctic stations of the high quality similar to the Antarctic data compiled by the Scientific Committee on Antarctic Research (SCAR) Reference Antarctic Data for Environmental Research (READER) project (Turner *et al.* 2004).

Table 1 gives some basic information for most of the meteorological stations in or near the sub-Antarctic. The data were obtained from a number of different sources, as noted with the table. The World Meteorological Organization (WMO) recommends the use of the period from 1961–1990 to calculate "climatological standard normals" for reference and comparison purposes (WMO 1988). For predictive purposes, such as the conditions most likely to be experienced, a more recent and shorter period (as little as 10 years) can provide adequate data (WMO 2007). In either case, the homogeneity of the observations is important, and the calculated statistics will only truly apply at the site where the observations were made. For the current study, complete data were not obtained from either the standard 1961–1990 period or a shorter period; there was not a chance to test the homogeneity of the data; and there are known to be marked topographic influences, with many of the meteorological stations located close to sea level in relatively protected areas. For these reasons, the climate statistics (mean temperatures of the coldest and warmest month and the average annual precipitation) are intentionally shown in table 1 to only a low precision. The presented values should thus be considered indicative only, and more precise values can be derived only after a detailed study.

Surface air temperatures of the sub-Antarctic

The sub-Antarctic climate is more or less fixed to mean monthly air temperatures between about –5°C and +15°C. As mentioned, this is a slightly wider band than that proposed by Stern *et al.* (2000), but allows for inclusion of the relatively mild islands such as Île Amsterdam, and also of contrasting below zero mean winter temperatures near 60°S. Figure 3 shows the annual mean surface temperature across the globe, synthesised from a variety of sources. The 60°S and 40°S latitudes are shown on this figure to highlight that the strongest meridional sea-level surface temperature gradients in the Southern Hemisphere occur in the sub-Antarctic (although the strongest topographical surface temperature gradients are located in the latitude band 80°S to 60°S by virtue of the very high terrain of the Antarctic Continent).

Orcadas, located just south of 60°S and strictly not part of the sub-Antarctic, is nonetheless useful in providing

TABLE 1
Basic climate statistics from locations within or near the sub-Antarctic

Location	Latitude	Longitude	Elevation	Mean temperature of coolest month	Mean temperature of warmest month	Mean annual precipitation	Source	Years used
Marion Island	47°S	38°E	22	+4	+8	2400	SAWS	1961–1990
Îles Crozet (Alfred Faure)	46°S	51°E	146	+3	+8	2200	MF	1980–2006
Îles Kerguelen (Port-aux-Français)	49°S	70°E	29	+2	+9	700	MF	1980–2006
Heard Island (Atlas Cove)	51°S	73°E	3	0	+4		ABOM	1997–2007
Île Amsterdam (Martin-de-Viviès)	38°S	78°E	27	+11	+18	1100	MF	1980–2006
Macquarie Island	54°S	159°E	6	+3	+7	900	ABOM	1961–1990
Campbell Island	53°S	169°E	19	+5	+10	1300	NIWA	1961–1990
Chatham Island	44°S	177°E	29	+8	+15	850	NIWA	1961–1990
Punta Arenas (Carlos Ibañez)	53°S	70°W	37	+1	+11	350	DMC	1961–1990
Ushuaia	55°S	68°W	16	+1	+10	500	SMN	1961–1986
Falkland Islands (Mt Pleasant)	51°S	59°W	74	+2	+11	600	UKMO	1989–2006
South Orkney Islands (Orcadas)	60°S	45°W	6	–10	+1	650	SMN	1961–1982
South Georgia (Grytviken)	51°S	37°W	3	–2	+5	1600	BAS	1951–1980
South Sandwich Islands (South Thule)	59°S	27°W	78	~ –5	~ +1		TT	1995–2005
Gough Island (Transvaal Bay)	40°S	10°W	54	+9	+15	3200	SAWS	1961–1990

Elevation in metres above sea level. Temperature in °C. Precipitation in millimetres. See text for details and discussion.
Data sources: ABOM–Australian Bureau of Meteorology; BAS–British Antarctic Survey; DMC–Dirección Meteorológica de Chile; MF–Meteo France; NIWA–New Zealand National Institute of Water and Atmospheric Research; SAWS–South African Weather Service; SMN–Servicio Meteorológico Nacional (Argentina); TT–TuTiempo (2007), note that data are very limited; UKMO–United Kingdom Met Office.

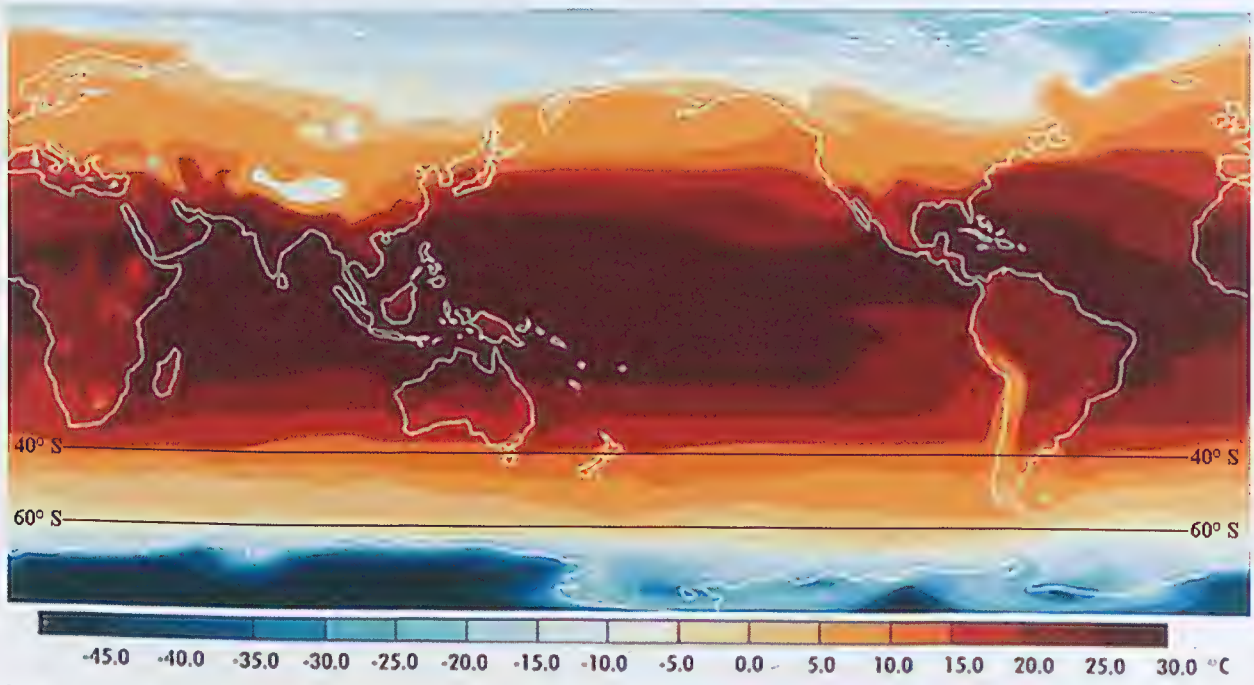

FIG. 3 — Thirty-year (1961–1990) annual mean surface temperature. Adapted from the Australian Bureau of Meteorology (2003).

observations at the southern edge of the region and on the eastern side of Drake Passage. Mean monthly air temperatures range from about –10°C in July to +1°C in February (table 1). Grytviken, on South Georgia, could be considered more typical of the colder areas of the sub-Antarctic, with mean monthly air temperatures ranging between about –2°C and +5°C. Îles Crozet is typical of more moderate sub-Antarctic areas with mean monthly air temperatures between about +3°C and +8°C.

On Chatham Island, mean monthly air temperatures range between about +8°C and +15°C (table 1), placing it within the bounds of the sub-Antarctic climate considered here, although New Zealand does not consider it to be sub-Antarctic (Department of Conservation 2007). At a latitude of around 37°S, the sub-Antarctic island (SCAR 2007) of Île Amsterdam's mean monthly air temperature in February is as high as +18°C; indeed Guinet *et al.* (1994) referred to Île Amsterdam as "subtropical". However, with Île Amsterdam's August mean monthly temperatures close to +11°C, it would seem likely that the islands north of the South Subtropical Front are in a regime that derives its sub-Antarctic status from a combination of meteorological considerations and sub-Antarctic-dependent fauna and flora species. For example, Guinard *et al.* (1998) refer to an increase in the population of Sub-Antarctic Fur Seals (*Arctocephalus tropicalis* (J.E. Gray, 1872)) on the island coincident with a significant decrease in mean sea surface temperature in the area.

Surface wind and waves of the sub-Antarctic

Describing the characteristics of the wind field of a geographical area as large as the sub-Antarctic from land-based point observations has challenges. In particular, the positioning of the wind-measuring equipment relative to the topography of the surrounding features is crucial. For example, Beggs *et al.* (2004, p. 295) reported "considerable spatial variability" in wind speed direction on Heard Island.

Remote sensing from satellites presents the opportunity of a more homogenous view. For example, Young & Holland (1996) produced an atlas of wind and wave height data based on data from satellites; an extract is shown as figure 4. The annual median wave height generally exceeds 2 m south of the North Subtropical Front and 2.5 m south of the South Subtropical Front. The sub-Antarctic is characterised by appreciable sea wave activity: the peak in annual median wave height is over 4 m, in the southeast Indian Ocean, while a substantial part of the oceans of the sub-Antarctic have median annual wave heights over 3.5 m (fig. 4A).

Driving these waves are the winds known as the "Roaring Forties" and the "Furious Fifties". These show up clearly in figure 4B, with annual median wind speeds exceeding 8 m/s for most of the sub-Antarctic. The strongest wind speeds occur over the southern Indian Ocean, with secondary maxima over the southern Pacific Ocean and the lightest speeds in the lee of the southern South American, and to a lesser degree, over the central southern Pacific Ocean. Figure 4B, whilst depicting annual data, is also representative of many individual months.

The Young & Holland (1996) data also show a clear seasonal cycle in wind speeds over the sub-Antarctic. The lightest winds occur in January with most wind speeds in the range 6–12 m/s, while the strongest winds occur during the July–August period when speeds exceed 10 m/s for the majority of the sub-Antarctic region and when mean speeds in the order of 15 m/s are more prevalent. The spring and autumn periods are transitional between the relatively light winds of summer and the winter storms. Mean winds tend to be stronger in spring than in autumn, presumably due to the enhanced thermal gradient in spring when the sea-ice sheet surrounding the Antarctic continent reaches its maximum extent and the continental land masses of Australia, South Africa and South America are beginning to warm.

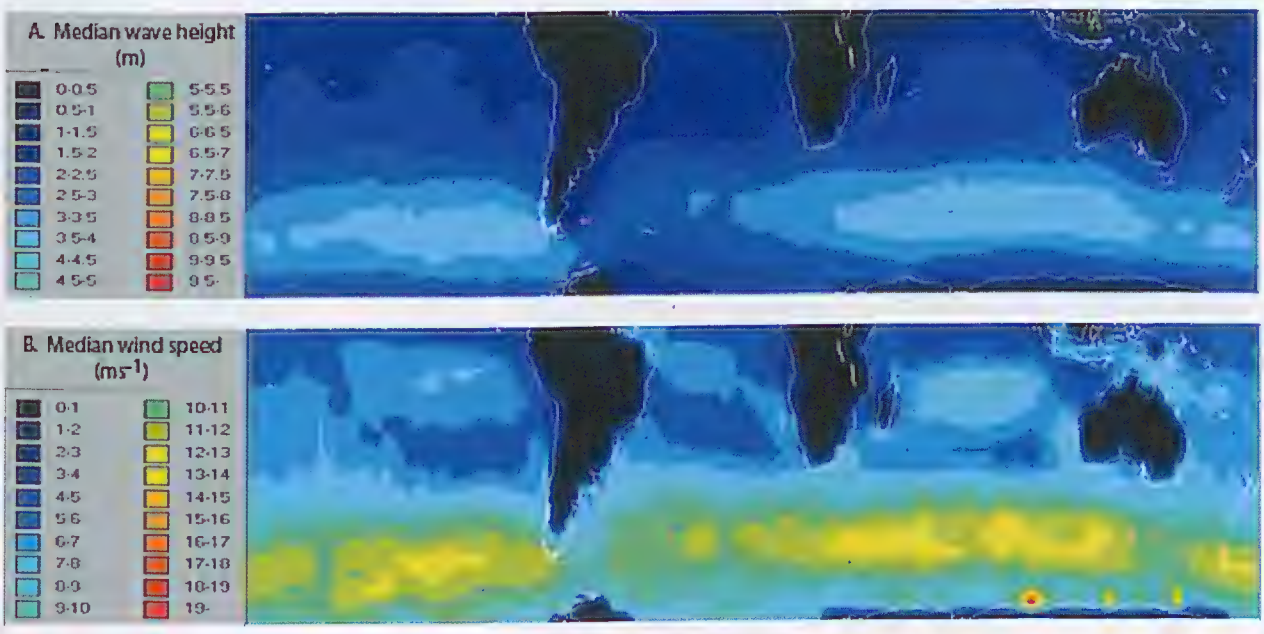

FIG. 4 — (A) Annual median wave heights; (B) annual median wind speeds (bottom) for the Southern Hemisphere. Adapted from Young & Holland (1996).

Precipitation over the sub-Antarctic

As with wind, characterising the precipitation regime of the sub-Antarctic is problematical. Precipitation measurement itself is not straightforward, especially where the water can fall as liquid (rain, mist, etc.) or solid (snow and hail), or a combination of both phases, all in a windy environment. Not only is it difficult to separate free-falling precipitation from that which is wind-blown (e.g., raised snow) but the performance rain gauges is complex and variable in these circumstances (Yang *et al.* 1998). Given these difficulties, and that the precipitation gauges in the sub-Antarctic are confined to the small amount of land, satellite measurements probably hold the most promise for reliable region-wide estimates. Therefore the data presented here should be considered indicative only, and a more definitive description may need to await the outcome of initiatives such as the US National Aeronautics and Space Administration (NASA) Global Precipitation Measurement mission (NASA 2007).

Conventional land-based and satellite techniques give an annual average precipitation for most of the sub-Antarctic in the range of 750 to 1500 mm (fig. 5). The persistent westerly winds ensure the west coasts of the landmasses tend to have higher precipitation than either the eastern coasts or the surrounding ocean. A clear example is the west coast of southern South America, but a similar effect appears even on small land masses: the precipitation on Marion Island in table 1 exceeds that for the nearby ocean in figure 5.

Not evident in figure 5 are the various precipitation types common to the sub-Antarctic, and thus the attendant measurement difficulties. For example, Bouvetøya is 93% glaciated (TheFreeDictionary 2007) while 80% of Heard Island is permanently covered by snow and ice (Australian Government 2007). This is indicative of the mostly frozen nature of precipitation at high-latitude parts of the sub-Antarctic especially during the colder months, the orographic nature of these particular islands and their location south of the Antarctic Polar Front (fig. 1). Macquarie Island, at a similar latitude to Bouvetøya and Heard islands, is of much lower average elevation (200–350 m above sea level (Australian Antarctic Division 2007)); it is also located north of the Polar Front (fig. 1). Macquarie Island has no permanent snow cover although frozen precipitation does occur at the observation station (6 m elevation).

Whilst each location in the sub-Antarctic will have its own precipitation regime, Macquarie Island would be arguably representative of many areas between the Polar and sub-Antarctic fronts and so it is worth noting the following extracts from the Australian Bureau of Meteorology (2007):

- *Rain and Drizzle*: Mean annual precipitation is 954 mm, and the median value is not much different at 958 mm. Autumn is slightly wetter than winter or spring, but all months receive rain. Heavy rain is quite rare, with only about one day in the average year receiving more than 25 mm. The wettest single day was in March 2001, with 52.8 mm. Such heavy rain has been known to trigger landslides on the island. The driest month on record was December 1959, with 16 mm, whilst the wettest was March 1988 with 181 mm. Measurable precipitation is recorded on an average of 313 days per year, or almost six days out of seven. This is fairly consistent across the year.
- *Snow and Hail:* Snowfall can occur at any time of the year, happening on about 80 days on average at sea level. It is least likely in January (less than one day on average) and most likely in September (almost eight days). A typical year would see up to half a dozen falls of around 10 cm depth at sea level. In most years the upper part of the plateau is covered in wet snow much of the time, particularly from May–October, with depths in level areas between one-half and one metre by the

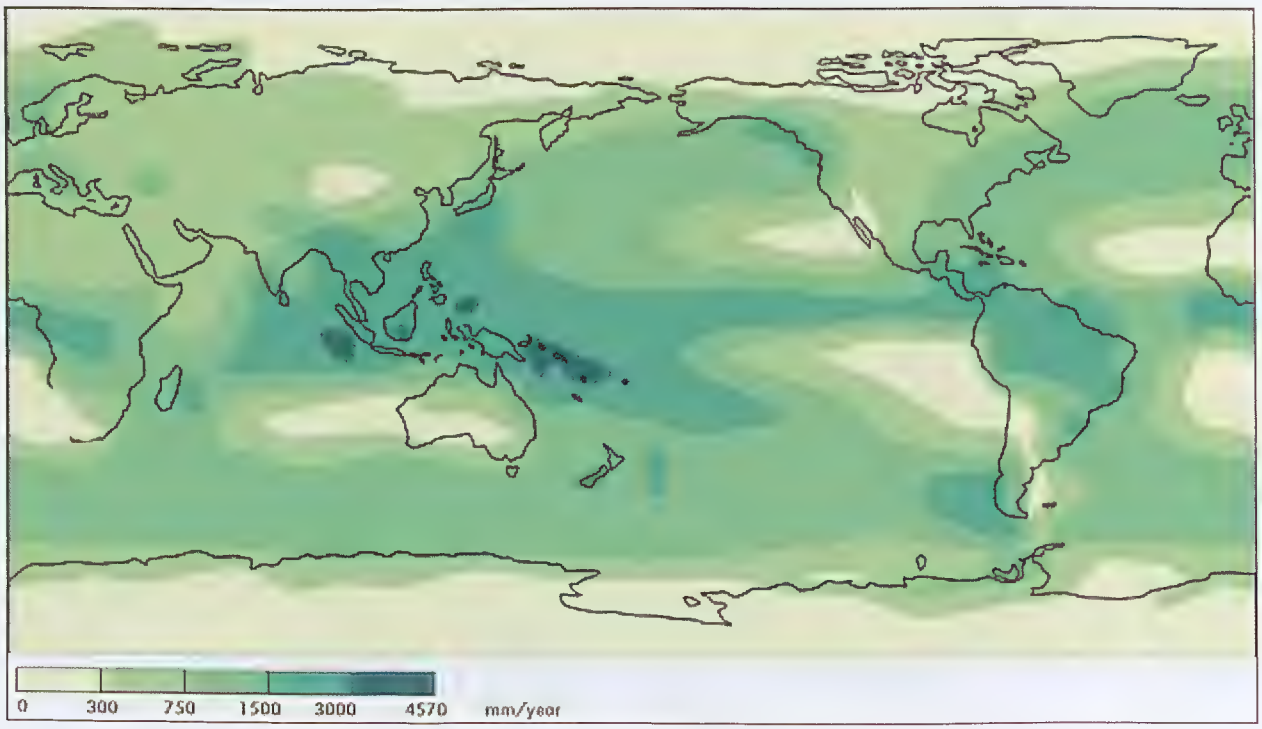

FIG. 5 — Thirty–year (1961–1990) annual precipitation (mm). From the Australian Bureau of Meteorology (2003).

end of the season. Hail, normally small in size, is also relatively common on the island, occurring on about 65 days a year on average. It is most likely in October and least likely in January. Thunderstorms are rare but do occur, averaging about 1 per year at the station.

Sub-Antarctic locations north of the sub-Antarctic Front will likely receive higher precipitation amounts as they are in a relatively warmer environment with more available precipitable water (Amenu & Kumar 2005), although they will still experience frozen precipitation forms. For example, as inferred from data reported by Turner & Pendlebury (2004), Transvaal Bay Station on Gough Island (just south of 40°S and 54 m above sea level) receives approximately three times the precipitation each year of Macquarie Island (just south of 54°S and 6 m above sea level), yet also annually experiences around 11 days of hail and about eight days of snow.

TELECONNECTIONS AND THE SUB-ANTARCTIC

The American Meteorological Society (2000, p. 759) defined a teleconnection as "a linkage between weather changes occurring in widely separated regions of the globe". Carleton (2003) summarised nine teleconnections which he considers to have important roles in the Southern Hemisphere, and some other important teleconnections have also been identified (for example, the Pacific Decadal Oscillation is discussed by Pezza *et al.* (2007)). El Niño-Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) appear to be the most important teleconnections affecting the sub-Antarctic.

Tropical effects on the sub-Antarctic

There are several studies relating ENSO events to the Antarctic, and Turner (2004) provided an excellent overview of many of these, but none is devoted to the sub-Antarctic. Yuan (2004) discussed physical mechanisms by which the El Niño and La Niña phenomena are thought to influence the "Antarctic Dipole" through effects on the regional Hadley Cell and the resulting jet streams. During an El Niño event the far southeast Pacific Ocean and adjacent Southern Ocean is colder with more storms and more sea ice, whilst the far southwest Atlantic Ocean/adjacent Southern Ocean is warmer with fewer storms and less sea ice. This dipole effect is reversed during La Niña events. To illustrate these effects, figure 6 is adapted from Yuan (2004) and shows conditions averaged over five El Niño events, particularly as they are manifested over the area of the Antarctic Dipole.

As may be inferred from Yuan (2004), the key driver of Antarctic Dipole characteristics in El Niño events is the positive sea surface temperature (SST) anomaly in the equatorial Pacific Ocean east of Colombia, Ecuador and Peru. This leads to several reinforcing factors: the meridional SST gradient increases which, together with increased vertical motion over the warmer equatorial waters, leads to a regional Hadley Cell that is stronger and more compact than average, with the Subtropical jet stream perturbed northwards over the central southern Pacific Ocean. A large-scale atmospheric wave pattern is set up by the vertical motions resulting from this SST anomaly, with the ascending air over the eastern equatorial Pacific perturbing the planetary-scale atmospheric waves. This leads to relatively high surface air pressure over the Bellingshausen Sea area ("H" in fig. 6). Moreover, the increased subsidence associated with the southern descending arm of the Hadley Cell circulation induces a stronger than average Ferrell Cell to the south: the low-level northerly airflow associated with the strengthened Ferrell Cell leads to warm air advection over the adjacent sub-Antarctic and higher southern latitudes and thus a decrease in sea ice in the Southern Ocean.

To the west of the Bellingshausen Sea (the region marked "Less Storms" in fig. 6), an increase in storm activity is likely as lows over sub-Antarctic waters are steered

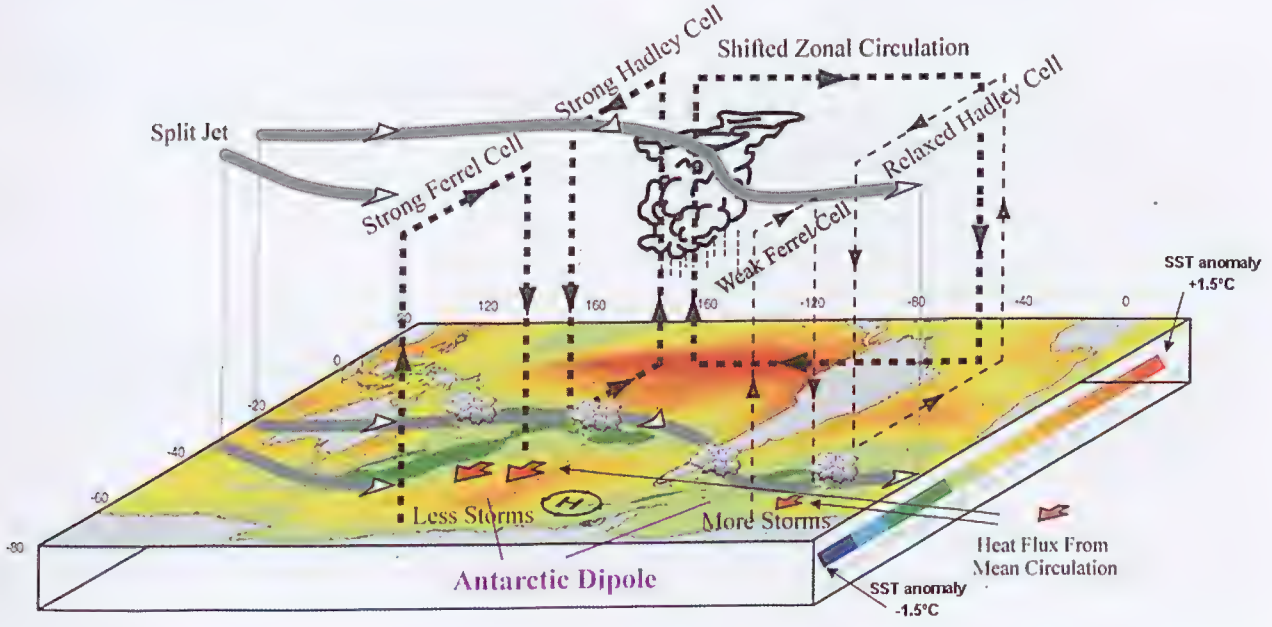

FIG. 6 — A schematic of mean conditions for five El Niño events as they impact on the Antarctic Dipole. Adapted from Yuan (2004).

southeastwards on the western side of the area of high pressure. Massom *et al.* (2004) describe a similar situation in East Antarctica.

The tropical Indian Ocean also has at least an indirect effect on the sub-Antarctic. The Indian Ocean Dipole (IOD) is a coupled ocean-atmosphere phenomenon characterised by SST cooling in the southeastern equatorial Indian Ocean and SST warming in the western equatorial Indian Ocean (or the converse). The IOD is an area of active research, including not only its direct effects but also links it has to other teleconnections such as ENSO. Behera & Yamagata (2003), for example, report on statistically significant associations with the IOD and sea-level pressure evolution from the western tropical Indian Ocean to the western tropical Pacific region.

Another example of the influence of the tropical Indian Ocean on high southern latitudes is the Madden-Julian Oscillation (MJO) which manifests itself in the atmosphere as a slow (order of one to two months) eastward propagation of disturbances (such as tropical convection/precipitation) with maximum amplitudes in the eastern Indian Ocean (Madden & Julian 1971, 1994). Lau & Chan (1986) noted that the MJO "is the strongest signal so far found in the intraseasonal variability of the tropical atmosphere" while the ENSO is "known to be the single most prominent signal in the interannual variability of the earth's climate". There is evidence that both the IOD and the MJO indirectly affect the sub-Antarctic, via their associations with ENSO.

Matthews & Meredith (2004) reported on a more direct link with the MJO and high southern latitudes. They show that during the southern winter, about seven days after the MJO convection peaks over the equatorial Indian Ocean, there is a peak in the surface westerly wind flow over high southern latitudes, including roughly the southern half of the sub-Antarctic. This is followed three days later by a maximum in the Antarctic circumpolar (ocean) transport. The physical mechanisms driving this response have similarities with the ENSO impacts on the Antarctic Dipole referred to earlier: upward vertical motion over the equatorial tropics disturbs the atmosphere to the south.

Southern Annular Mode

While ENSO is the most famous teleconnection, there has been increasing interest in examining the characteristics of "annular modes". Thompson (2007) had a web site devoted to the topic. The Southern Annular Mode, alternatively known as the Southern Hemisphere Annular Mode, the Antarctic Oscillation (Gong & Wang 1999) or the High-Latitude Mode (Kidson & Watterson 1999), refers to atmospheric mass exchange between middle and high latitudes as weather systems evolve on weekly to monthly timescales. Thompson & Solomon (2002, p. 896) described the SAM as "a large-scale pattern of variability that dominates the SH extratropical circulation on week-to-week and month-to-month timescales". The anomalies in mass tend to occur in zonal or annular bands; Marshall (2003, p. 4134) noted the SAM is "essentially a zonally symmetric or annular structure, with synchronous anomalies of opposite signs in Antarctica and the midlatitudes".

Indices of SAM tend to be constructed to reflect anomalies on monthly, seasonal or annual timescales, with various methods of indexing the related mass exchange. Gong & Wang (1999) described an "Antarctic Oscillation Index", using USA National Center for Atmospheric Research (NCAR)/ National Centers for Environmental Prediction (NCEP) (Kalnay *et al.* 1996) modelled reanalysis data at 40°S and 65°S. Marshall (2003) followed Gong & Wang (1999) but calculated a SAM index (here denoted SAM*i*) using observed mean sea level pressure (MSLP) data from stations located around, or very close to, each of the 40°S and 65°S latitude bands, as:

$$SAMi = P^*40^oS - P^*65^oS$$

where P* is the normalised (and unitless) mean monthly, seasonal, or annual zonal MSLP.

Marshall (2007) maintained an observations-based SAM index web site from which the locations of the 12 stations used to define his index (six at 40°S and six at 65°S) may be obtained, along with the normalised SAM*i* data and various monthly, seasonal and annual figures (see fig. 7) showing trends in SAM*i*.

In a low-index phase (negative values of SAM*i*), there is anomalously high pressure at 65°S and anomalously high pressure at 40°S, while a high-index phase (positive values of SAM*i*) has anomalously high pressure at 40°S and anomalously low pressure at 60°S. Matthews & Meredith's (2004) work on the MJO is an example of the forcing of the high-index state of SAM resulting in above average westerly winds over the sub-Antarctic. Further discussion on the role of the Southern Hemisphere Annual Mode in the climate of the sub-Antarctic is deferred until the next section where it may be inferred that a high-index state SAM is associated with relatively dry conditions over some northern parts of the sub-Antarctic, and wetter, windier conditions towards more southern parts.

EVIDENCE OF CLIMATE CHANGE IN THE SUB-ANTARCTIC

There seems little doubt that the climate of the sub-Antarctic is changing, at least in the short to medium term. Glacial retreat on sub-Antarctic islands is an indicator of such change (Budd 2000, Hall 2002). For example, Thost (2005, p. 34) reported, "Research has shown that Brown Glacier on sub-Antarctic Heard Island is retreating rapidly. It suggests that local climatic conditions are continuing to change rather

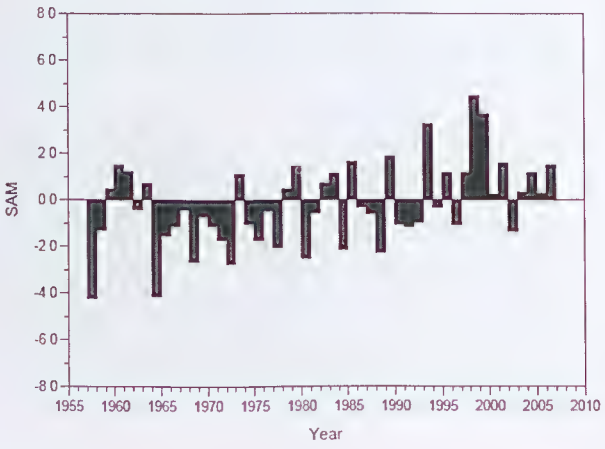

FIG. 7 — Annual SAMi for the period 1957–2006. Adapted from Marshall (2007).

than stabilise". Thost attributes the retreat of this glacier (at an average annual rate of 21 m) to an increase of (local) temperatures of about 1°C since 1950.

Jacka *et al.* (2004) reported on surface temperature changes over the period 1949–2002 for a selection of Southern Hemisphere stations, most of which are located in the Antarctic or in the non-tropical oceans, including 13 which are in, or very close to, the sub-Antarctic. Of these 13 stations, all but Punta Arenas had reported an increase in mean annual surface air temperature over the period examined. The surface air temperature trends for Marion and Gough islands are given by Jacka *et al.* (2004) as 2.8 and 0.4°C per 100 years respectively. These trends are broadly consistent with the SST trends presented by Mélice *et al.* (2003), which show warmings of about 3.0°C per 100 years in the waters surrounding Marion Island and 1.0°C per 100 years near Gough Island.

Bindoff *et al.* (2007, p. 401) noted that "The upper ocean in the [Southern Hemisphere] has warmed since the 1960s, dominated by changes in the thick near-surface layers ... just north of the Antarctic Circumpolar Current". Gille (2002) presented evidence that, within observational error, the surface warming reported by Jacka *et al.* (2004) matches warming which has occurred in middle depths (700–1100 m) of the mid- to high-latitude southern oceans, with the most rapid mid-depth ocean warming being within the sub-Antarctic Front. Thus, not only is there evidence of air and sea-surface temperature warming in the sub-Antarctic, but the warming extends to considerable depths of the sub-Antarctic oceans.

SAM and sub-Antarctic climate change

Figure 7, adapted from the annual SAM*i* data of Marshall (2007), shows a marked change from generally negative values up to the mid-1970s to generally positive values from the mid-1990s. That is, there has been an increase in atmospheric mass around 40°S relative to that at 65°S. This shift in mass, and the implied circulation changes, appear to have had direct effects on the climate of the sub-Antarctic.

Goodwin *et al.* (2004) presented ice core data, with monthly resolution spanning the years from 1300 to 1995. By linking May-June-July sodium concentrations with the SAM for the same period, they were able to create a proxy SAM index spanning almost 700 years. They suggested that the SAM was in a more negative index state prior to 1600, and that the very recent trend towards a positive index state is "part of multi-decadal variability that characterises the past 700 years"; that is, the trend of the past few decades was part of natural variability.

Marshall *et al.* (2004), however, noted that since 1964 statistically significant positive trends in SAM only occur in the annual, summer (December–January–February), and autumn (March–April–May) series. Figure 8 shows the Marshall (2007) SAM*i* for the four seasons, with little trend evident in winter or spring. Moreover, Marshall *et al.* (2004) presented data from a 1000-year climate model run, and separately, four runs from 1860 with varying sources of external forcing. These authors reported that the post-1965 trends in SAM exceed the natural model climate variability, and that "non-linear combination of anthropogenic and

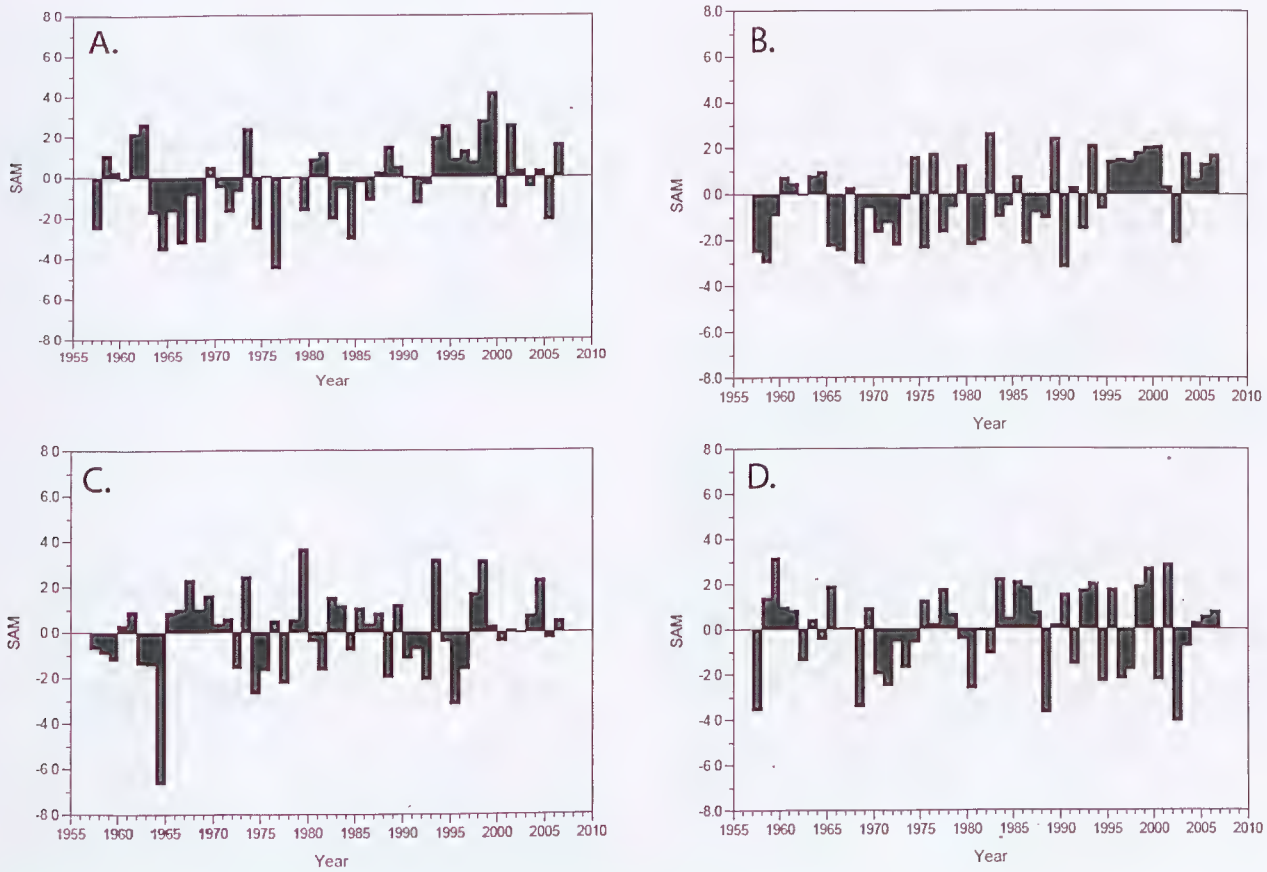

FIG. 8 — Seasonal SAMi for the period 1957–2006: (A) Summer (Dec, Jan, Feb); (B) Autumn (Mar, Apr, May); (C) Winter (Jun, Jul, Aug); (D) Spring (Sept, Oct, Nov). Adapted from Marshall (2007).

natural forcings is responsible for the observed changes in the SAM since the mid-1960s" (Marshall *et al.* 2004).

Recent trends at high latitudes were attributed by Thompson & Solomon (2002) to the effects on SAM of stratospheric ozone depletion. Figure 9A shows recent changes in surface air temperatures and 925 hPa winds in the austral summer and autumn, and figure 9B shows how much these changes can be attributed to changes in SAM. The focus of Thompson & Solomon (2002) was Antarctica and, in particular, the Antarctic Peninsula, so temperature data are not shown for sub-Antarctic stations away from these areas. Nevertheless, it is evident that increased low-level westerly airflow has occurred over the sub-Antarctic and that part of the sub-Antarctic near Drake Passage has warmed in summer and autumn in line with increases in SAM*i*. They concluded around 50% of the increase in surface air temperature observed at the tip of the Antarctic Peninsula could be explained by changes in SAM, and that a high-index state of SAM is consistent with observed ozone depletion. They also noted that this implies that there are other "climate change mechanisms" operating over this region.

Fyfe (2003) provided further evidence that changes have occurred in the sub-Antarctic and the Southern Ocean, using NCEP/NCAR reanalysis data from 1960–1999. In this period, he found: a shift southwards of the baroclinicity of the mid- to high-latitude atmosphere; a decrease in the number of cyclones over the sub-Antarctic ocean (and an increase over the Southern Ocean); and a decrease in the mean depth of cyclones but with numbers of "shallow" cyclones decreasing more than the numbers of deeper cyclones.

Climate change on Marion Island and Macquarie Island

Smith (2002) has demonstrated how the climate of Marion Island has changed since records began on the island in 1949: he reported that simple linear fits to the data show a 0.04°C per year increase in annual mean temperature over the period 1969–1999; an increase of 3.3 hours of bright sunshine per year over 1951–1999; and a decrease of 25 mm per year in annual total precipitation.

There is also evidence (Adamson *et al.* 1988, Jacka *et al.* 2004) of climate change on Macquarie Island, from where continuous weather records are available since 1948. The Macquarie Island data indicate that the surface air temperature has increased, although perhaps not in the past two decades; but rainfall has markedly trended upwards: 2005 was the wettest year on record at the station.

Figure 10 shows the mean annual temperature anomalies (compared to 1961–1990 normals) for both Marion and Macquarie islands. Also shown is a smoothed line produced using a "loess" (local estimator) smoother with an effective span of 20 years (R Development Core Team 2006). Care must be taken in interpreting the shape of the line at each end, but it gives a good overall indication of underlying trends in the data. The warming at the Marion Island station is quite clear, whereas at the Macquarie Island station the trend since about 1980 is more ambiguous, with a number of relatively cold years observed.

Recent trends in precipitation for these two island stations are clearly opposite to each other. Figure 11 shows, for each station, the fraction of annual rainfall compared to the 1961–1990 normals. Marion Island station has become drier whilst Macquarie Island station has become wetter. One possible explanation for the changes at the two islands is the southward shift in tropospheric baroclinicity reported by Fyfe (2003) — his figure 3 shows analysed and projected southward displacement of the maximum in 500 hPa temperature gradient averaged on a decadal basis and zonally around the Southern Hemisphere. The 500-year

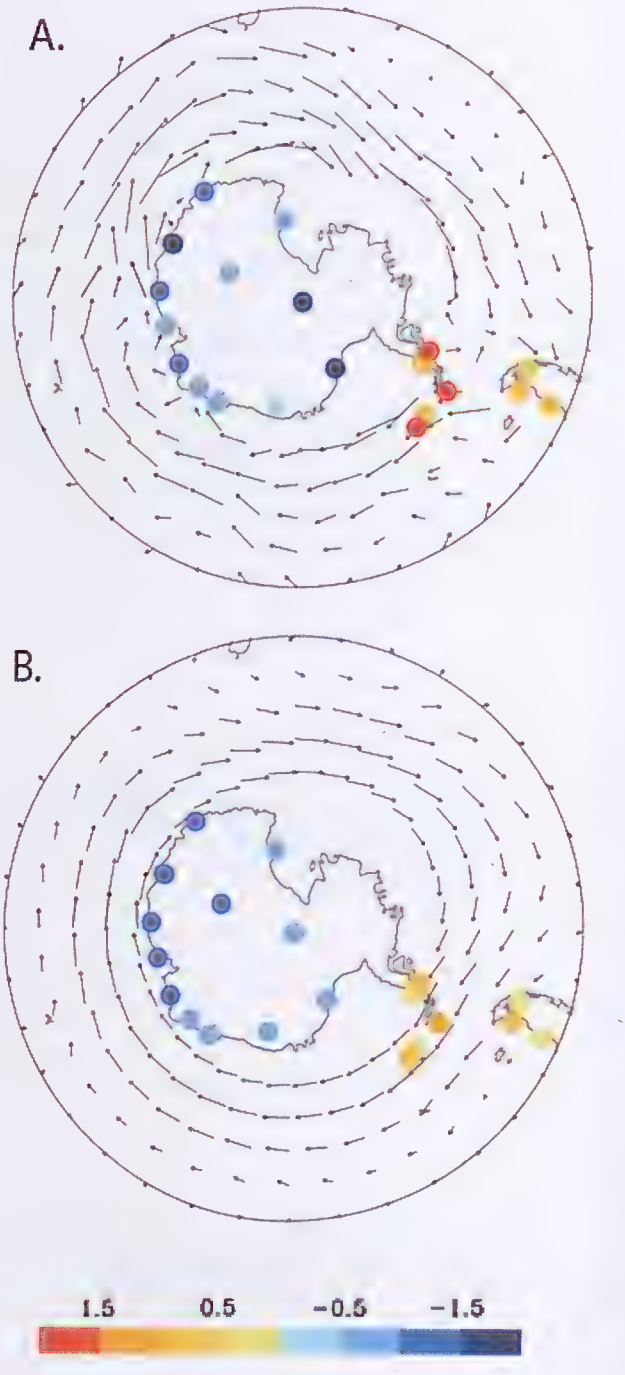

FIG. 9 — (A) Observed December–May trends in surface temperature over the period 1969–2000 and 925 hPa winds over the period 1979–2000; (B) the contribution of SAM to the observed trends in (A). The key (middle) is temperature change in °C per 30 years. The longest vector in (A) and (B) represents 4 m/s. After Thompson & Solomon (2002).

control simulation used by Fyfe (2003) had the maximum in this parameter at approximately 47°S. By inference, this may have seen the latitude of peak intensity of rain-bearing systems moving away from latitudes typical of Marion Island (at around 47°S) towards latitudes represented by Macquarie Island (around 54°S). Another possible explanation, at least for Marion Island, is the suggestion by Rouault *et al.* (2005) that the local changes on that island are due to a phase shift in the semi-annual oscillation in the Southern Hemisphere circa 1980.

However, the SAM may be also implicated. Figure 12 is adapted from Thompson & Wallace (2000) and shows mean zonal flow anomalies and mean meridional circulation anomaly vectors regressed on SAM for November based on monthly data from 1958 to 1997. This is a November case, but it serves as an analogy for high-index state of SAM, showing Marion Island in a region of nett subsidence while Macquarie Island is in a region of increasing westerly winds (potentially bringing more moisture).

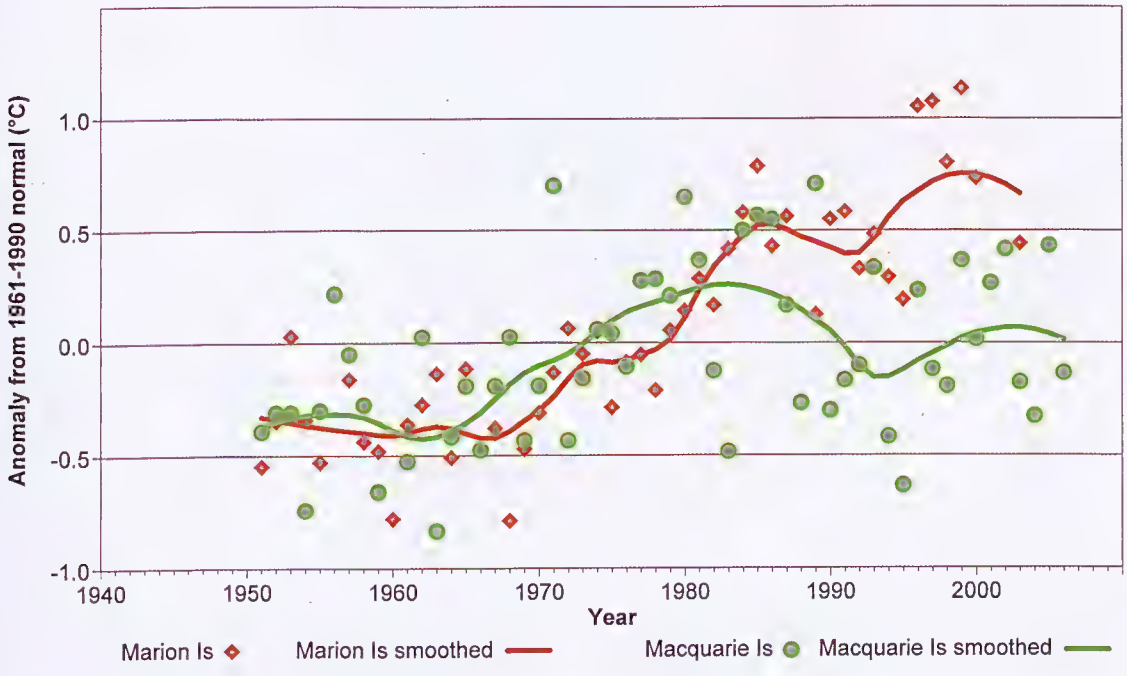

FIG. 10 — Observed mean annual temperature anomalies at Marion and Macquarie islands, relative to the 1961–1990 normals. The dots are the observed values for each year, with the smoothed lines produced using a "loess" smoother with an effective span of 20 years.

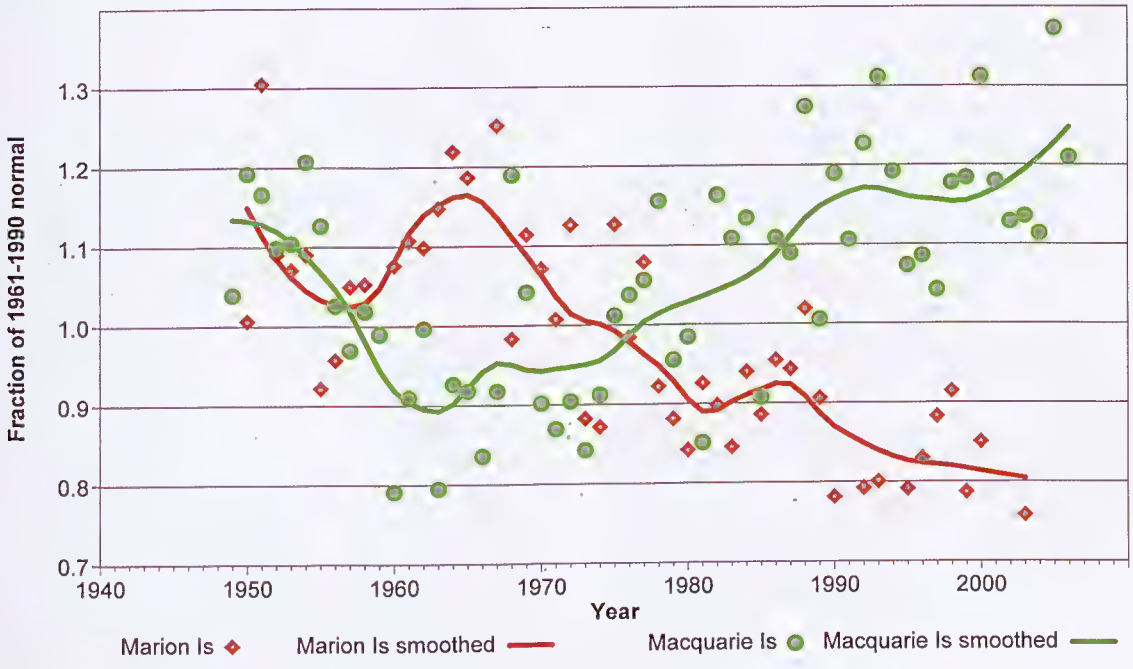

FIG. 11 — Observed total annual precipitation at Marion and Macquarie islands, as fractions of the 1961–1990 normals. The dots are the observed values for each year, with the smoothed lines produced using a "loess" smoother with an effective span of 20 years.

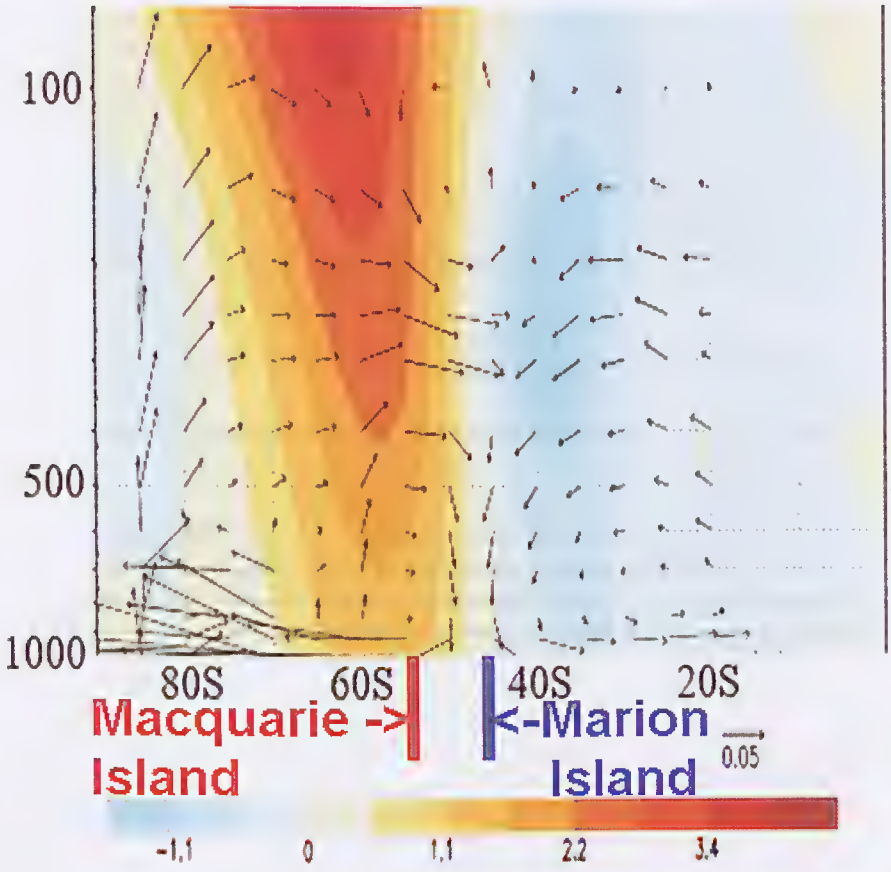

FIG. 12 — Mean cross-section (height scale in hPa) for the Southern Hemisphere of zonal–mean zonal flow anomalies (red represents westerly anomalies and the blue easterly anomalies in m/s) and mean meridional circulation anomalies (vectors: cm/s) regressed on SAM for November based on monthly data from 1958 to 1997. Adapted from Thompson & Wallace (2000).

Whinam & Copson (2006) implicated climate change on Macquarie Island in the decline, through desiccation of the island's sphagnum moss. They inferred that increasing wind speeds, rising surface temperatures and decreased rainfall will continue to place stress on this moss species. It is clear from the data presented in the current paper that mean annual temperatures on Macquarie Island appear to have little trend in recent decades, whilst annual precipitation at the station has actually increased in recent decades. Wind speeds may be slightly increasing over Macquarie Island due to an increasing SAM (figs 9 and 12, for example), so it is possible that there has been an increase in evapotranspiration. Alternatively, there may have been marked changes in the timing or severity of individual weather systems, which has increased stresses on the moss.

THE SUB-ANTARCTIC INTO THE TWENTY-FIRST CENTURY

At time of writing, the Intergovernmental Panel on Climate Change (IPCC) was finalising its Fourth Assessment Report "Climate Change 2007", also referred to as AR4 (and here termed IPCC-AR4). The IPCC Working Group 1 has released its report on the physical basis upon which AR4 is based (Solomon *et al.* 2007). The earlier allusion to observed warming in the upper levels of the oceans of the Southern Hemisphere being dominated by sub-Antarctic Mode Water (Bindoff *et al.* 2007) is one of the few direct references to the sub-Antarctic in Solomon *et al.* (2007). Nonetheless, inferences may be made from the global climate and regional climate projections in that report.

The bases for IPCC-AR4 Global Climate Projections are given in Meehl *et al.* (2007) with IPCC-AR4 Regional Climate Projections being discussed by Christensen *et al.* (2007) these being Chapters 10 and 11 of Solomon *et al.* (2007) respectively. Inferences on pattern changes in the twenty-first-century sub-Antarctic zonally averaged atmospheric and oceanic temperatures, surface temperature, precipitation, sea level air pressure and cloud cover may be obtained from Meehl *et al.* (2007). Slightly more detailed information on precipitation changes may be obtained from Christensen *et al.* (2007). Given that the projections are based on a subset of the IPCC Special Report on Emission Scenarios (Nakicenovic & Swart, 2000) the reader is encouraged to refer to the original references for the nuances behind the various scenarios modelling. However, it would seem that the overall trends for each parameter are similar for each scenario, varying in amount as projections extend forward in time through the twenty-first century.

Inferences of note (relative to a 1980–1999 reference period) are:

- If zonally-averaged, a steady warming seems likely in the sub-Antarctic oceans over most depths, but particularly to a depth of 1000 m, where, in the A1B scenario, the 2080–2099 sub-Antarctic oceans will be 0.5–1.5°C warmer (Meehl *et al.* 2007, their fig. 10.7).
- Over the sub-Antarctic as a whole, and for all three scenarios, surface air temperature changes of 0.0–1.0°C warmer are indicated by the period 2011–2030. However, for the periods 2046–2065 and 2080–2099 while the results for the three scenarios show similar trends, the magnitudes of the changes diverge more widely, with the "low" emission scenario indicating

conditions being 0.5–1.5°C warmer by the period 2046–2065 but the "medium" and "high" scenarios (combined) indicate warming in the range 1.0–3.0°C by the period 2080–2099 (Meehl *et al.* 2007, their fig. 10.8).

- In the "medium" scenario (A1B), by the end of the twenty-first century, south of about 40–45°S latitude austral winter precipitation increases by fractions of a millimetre per day, although a slight drying is indicated on the eastern side (lee in the predominant westerlies) of the south of South America. Sub-Antarctic areas north of about 40–45°S are generally drier in the period 2080–2099 compared to 1980–1999 (Meehl *et al.* 2007, their fig. 10.9; Christensen *et al.* 2007, their fig. 2).
- Austral summer precipitation projections for the A1B scenario and the same timeframes suggests that the area of drying extends southwards towards 50°S, and significantly, over much of the land areas of the sub-Antarctic, with the exception perhaps of Macquarie Island and the sub-Antarctic islands of New Zealand (Meehl *et al.* 2007, their fig. 10.9; Christensen *et al.* 2007, their fig. 2).
- For the A1B scenario, a steady increase in the positive phase of the SAM is indicated with, by 2080–2099, higher sea-level pressures over the sub-Antarctic north of about 45–55°S and lower sea level pressures south of this latitude band.

As may be inferred from the literature such as that of Whinam & Copson (2006), these changes may have major effects on the biology of the sub-Antarctic islands. Impacts might also be expected on sub-Antarctic parts of South America. Vera *et al.* (2006) noted some inconsistencies in the models used for the IPCC-AR4, but there is a consensus for decreased precipitation along the southern Andes for all seasons. There may well be effects on human activity in the area too, not least on the shipping which plies Drake Passage serving Antarctic tourism. The Antarctic and Southern Ocean Coalition & United Nations Environment Programme (2005) reported that 90% of the Antarctic tourist shipping departs for the Antarctic Peninsula from (sub-Antarctic) Ushuaia. As noted above, the positive phase of the SAM is expected to increase: this implies increased westerly winds which may well impact on shipping. Moreover, Meehl *et al.* (2007, p. 751) noted that "Model projections show fewer mid-latitude storms averaged over each hemisphere, associated with the poleward shift of the storm tracks that is particularly notable in the Southern Hemisphere, with lower central pressures for these poleward-shifted storms. The increased wind speeds result in more extreme wave heights in those regions."

Fyfe (2003) included a run of a global climate model for the period 1850–2100 using an ensemble of three transient climate change simulations, and post-1990 the IS92a ("business-as-usual") scenario (the Canadian Centre for Climate Modelling and Analysis (2006) provided a succinct comparison of the IS92a scenario and the IPCC A2 scenario). The results were generally consistent with those seen in Fyfe's findings in the NCEP/NCAR re-analysis data from 1961–1990: a southward shift in baroclinicity, and a decrease in sub-Antarctic cyclone activity.

Similarly, Yin (2005) discussed the output of 15 different coupled general circulation models run in experiments for IPCC-AR4 and reports that, for the Southern Hemisphere, the model consensus for the twenty-first century is that the following seems likely:

- consistent poleward shift in storm tracks
- poleward shift of midlatitude baroclinicity
- increase in meridional surface temperature gradient
- poleward shifts in wind stress and precipitation
- shift towards high-index SAM.

It is salient to note that several of the significant projections presented by IPCC-AR4 are consistent with observed trends recounted here. Increasing surface and submarine temperatures, changes in precipitation, and a high-index state of the SAM, all suggest that the projected climate changes of the twenty-first century are already under way for much of the sub-Antarctic.

CONCLUSION

By any measure the sub-Antarctic is an important region of the world. It is host to the Antarctic Circumpolar Current and a large portion of the extra-tropical atmospheric mass oscillation represented by the Southern Annular Mode.

There is clear evidence that the climate of the sub-Antarctic is changing, at least in the short term, and that human-induced greenhouse gases and ozone depletion are part of the cause (Fyfe & Saenko 2005). However, researchers are yet unambiguously to provide physical mechanisms for the changes observed.

Many studies into the sub-Antarctic climate are primarily interested in biology, with meteorology of importance only in its effects on the local flora and fauna. Without further research into the full extent of climate change and variability in the sub-Antarctic, many of the climatic impacts on biological systems will remain poorly understood. Underpinning this research will be the need for the creation of a robust databank of quality controlled sub-Antarctic meteorological data.

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INFLUENCES ON AND ORIGINS OF TERRESTRIAL BIODIVERSITY OF THE SUB-ANTARCTIC ISLANDS

by Peter Convey

(with one text-figure and five tables)

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The "sub-Antarctic" is a region of the planet characterised by small and extremely isolated island landmasses set in the vastness and harsh conditions of the Southern Ocean. Although there is no universally applicable definition of the sub-Antarctic, based on eco-climatic criteria (temperature and the presence/absence of trees or woody shrubs) a useful terrestrial biogeographic region can be defined that includes only those islands which lie close to the oceanic Antarctic Polar Frontal Zone (PFZ). These range between roughly 47°S and 54°S and include South Georgia in the South Atlantic sector of the Southern Ocean, Marion and Prince Edward islands, Îles Kerguelen and Crozet, and Heard and McDonald islands in the Indian Ocean sector, and Macquarie Island in the Pacific Ocean sector. These islands have widely differing origins and geological histories. This paper provides an overview of their biodiversity and of the major patterns in biogeography. The majority of islands are of relatively recent origin, and there are only very limited indications of a more ancient biogeographical history (Gondwana-breakup timescale) to be found in the contemporary biota. Amongst the sub-Antarctic biota, there are examples supporting two general hypotheses relating to their origin: the Insulantarctic and the multiregional scenarios. Sub-Antarctic terrestrial ecosystems, which are of biodiversity and conservation significance globally, are under considerable contemporary pressure through the twin influences of possible anthropogenic climate change, and the introduction and establishment of invasive non-indigenous species.

Key Words: biogeography, colonisation, dispersal, human impacts, climate change, South Georgia, Prince Edward Islands, Îles Kerguelen and Crozet, Heard Island, Macquarie Island.

INTRODUCTION

The "sub-Antarctic" is a region of the planet characterised by small and extremely isolated island landmasses set in the vastness and harsh conditions of the Southern Ocean. There is no universally accepted single geographic definition of the sub-Antarctic, although it is generally accepted as a meaningful term for a terrestrial biological region. For the purposes of this paper, the formulation of Smith (1984) will be used, which is based on eco-climatic criteria (temperature and the presence/absence of trees or woody shrubs), and includes only those islands which lie close to the oceanic Antarctic Polar Frontal Zone (PFZ). These range between roughly 47°S and 54°S and include South Georgia in the South Atlantic sector of the Southern Ocean, Marion and Prince Edward islands, Îles Kerguelen and Crozet, and Heard and McDonald islands in the Indian Ocean sector, and Macquarie Island in the Pacific Ocean sector. While limiting discussion here to these islands, it is only reasonable to recognise that they represent one stage of a continuum in environmental conditions between the more extreme environments of the islands and archipelagoes of the Continental and Maritime Antarctic (Balleny, Peter I Øya, South Shetland, South Orkney, South Sandwich Islands, Bouvetøya), and those of cold temperate oceanic islands and archipelagoes such as Diego Ramirez, the Falkland Islands, Tristan da Cunha, Gough Island, Amsterdam Island and New Zealand's shelf islands. Both the colder and warmer islands in these groups sometimes show considerable overlap in terms of common species or genera with those of the more tightly defined sub-Antarctic. This is demonstrated by bryophytes and lichens in relation with the maritime and continental Antarctic (Øvstedal & Smith 2001, Ochyra *et al.* in press), and by vascular plants, particularly "megaherbs", in relation with the New Zealand shelf islands (e.g., Fell 2002). In the literature, reference has been made at different times to some or all of these as "sub-Antarctic" (e.g., Dingwall 1995, Shirihai 2002).

The different sub-Antarctic islands have little in common in terms of their age and geological origin (table 1). The geological history of some areas has been contentious until recently (e.g., the Kerguelen Plateau, Wallace *et al.* 2002), and this remains the case for Îles Crozet (Craig 2003). Volcanism has been involved in the formation of many. Îles Kerguelen and Heard and McDonald islands are part of the Kerguelen Plateau, itself of Gondwanan age (although the islands are much younger) (Gladczenko & Coffin 2001). Marion and Prince Edward islands, and Îles Crozet, are shield volcanoes, which erupted 0.11–0.21 Ma and 0.2–9 Ma respectively (LeMasurier & Thomson 1990). South Georgia contains continental elements that are continuous with the Andes mountain chain of South America and the Antarctic Peninsula and Scotia Arc. Macquarie Island is an uplifted piece of largely intact seafloor ophiolite complex at the junction of the Indian-Australian and Pacific tectonic plates, and is currently thought to have emerged from the sea around 0.6 Ma (Adamson *et al.* 1995). Thus, with the exception of South Georgia, the majority of sub-Antarctic islands are substantially younger than the Southern Hemisphere continents, with the oldest being Îles Kerguelen at c. 39 Ma. Only two of the islands remain extensively glaciated today — Heard Island and South Georgia — although Pleistocene glaciation was also significant on Marion Island and Îles Kerguelen and Crozet.

The sub-Antarctic islands are often described as having "tundra" ecosystems. However, there are fundamental differences between these and the true tundra of the Arctic. These sub-Antarctic ecosystems experience a very strong oceanic influence and much reduced levels of seasonal

TABLE 1
General summary of the physical characteristics of the major groups of sub-Antarctic islands[1]

	Area (km^2)	Altitude (m)	Minimum age (myr)	Nearest continent (km)	Maximum glaciation
South Georgia	3755	2950	120	2210	complete
Marion	290	1230	0.45	1900	partial
Prince Edward	44	672	0.21	1900	no
Crozet	356	1090	0.4–8.75	2740	minor
Kerguelen	7200	1840	30	4110	almost total
Heard	368	2745	20	4570	complete
McDonald	2.6	230	0.079	5000	minor
Macquarie	128	433	0.6	990	none

[1] Data from Chown *et al.* (1998).

TABLE 2
Typical air temperature ranges experienced in summer and winter in the three commonly-recognised Antarctic and two Arctic biogeographical zones

Zone	Months with positive mean air temperatures	Mean monthly air temperature range (°C)	Extreme air temperature range (°C)	Estimate of annual degree days above 0°C (based on mean air temperatures)
High Arctic	2 to 4	–34 to +5	–60 to + 20	50–350
Low Arctic	4	–36 to + 11		600–900
Sub-Antarctic	6 to12	–2 to +8	–10 to +25	700–1700
Maritime Antarctic	1 to 4	–12 to + 2	–45 to +15	6–100
Continental Antarctic				
- coastal	0 to 1	–30 to –3	–40 to +10	0
- inland	0	<-50 to –10	<–80 to –5	0

environmental variation relative to other biogeographical regions in both the Antarctic and the Arctic (table 2). In particular this means that there is a relatively small difference between the warmest and coolest months — across all sub-Antarctic islands the warmest monthly mean temperature is only c. 7–8°C, while only those south of the PFZ (i.e., South Georgia and Heard Island) have monthly minima (slightly) below 0°C (Convey 1996a, Danks 1999). At the microhabitat level relevant to most biota, this thermal damping becomes even more apparent, with temperatures generally remaining positive year-round. Unlike the highly seasonal tundra ecosystems of the Arctic, permafrost is not present in the sub-Antarctic. An important biological consequence of these thermal regimes is that the invertebrate faunas of these ecosystems, in particular, have much reduced seasonal structure in their activity patterns and life histories (Convey 1996a, Davies *et al.* 2007). The relatively low latitude of the sub-Antarctic islands (between c. 47°S and 54°S, well north of the Antarctic Circle) also results in a longer growing season than is the case at higher latitudes (table 2), although their typically high cloud cover also reduces instantaneous radiation receipt. The islands also lie within the cyclonic belt of the Southern Ocean, experiencing typically high average wind speeds and precipitation levels.

BIODIVERSITY

The differences between levels of terrestrial biodiversity in the Arctic and sub-Antarctic are striking (tables 3 and 4), even in comparison with the environmentally much more extreme and also isolated High Arctic Svalbard and Franz Josef archipelagoes at approaching 80°N. While there are about 900 species of vascular plants in the Arctic there are only two on the Antarctic continent and a maximum of 40 on any single sub-Antarctic island (table 3). Likewise, the sub-Antarctic has no native land mammals, against the Arctic's 48 species. It is clear that the oceanic and atmospheric isolation of Antarctica and the sub-Antarctic (Barnes *et al.* 2006), in contrast with the continuous southwards continental connection of much of the Arctic, has been an important driver of the differences seen. Despite the apparent ease of access to much of the Arctic, a relatively low number of anthropogenically-introduced alien vascular plants or invertebrates are known at locations such as Svalbard (Rønning 1996, Coulson 2007), in comparison with the c. 200 species introduced to the sub-Antarctic by human activity over only the past two centuries or so (Frenot *et al.* 2005; table 5). This apparent contradiction may be explained because many of the sub-Antarctic "aliens" are cosmopolitan northern hemisphere and boreal "weeds" that have had greater opportunity to reach polar latitudes since deglaciation in the north than the south, either by natural means or during earlier phases of post-Pleistocene human colonisation.

TABLE 3
Levels of species diversity of four of the better-known groups of biota across the sub-Antarctic islands

	Higher Plants	Insects (not Collembola)	Seabirds	Land birds
South Georgia	25	21	26	2
Marion	23	19	27	1
Prince Edward	21	18	28	1
Crozet	> 19	> 44	> 33	2
Kerguelen	30	27	33	3
Heard	10	11	18	1
McDonald	5	6	9	1
Macquarie	40	20	23	0

TABLE 4
Species diversity in some of the main representative terrestrial groups of the sub-Antarctic biogeographical zone, in comparison with three Arctic locations[1]

Group	Sub-Antarctic	High Arctic (Svalbard)	High Arctic (Franz Josef Land)	Greenland
Rotifera	> 59	154		
Tardigrada	> 34	83		
Nematoda	> 22	111		
Platyhelminthes	4	10		
Annelida (Oligochaeta)	23	34		
Mollusca	3/4	0		2
Crustacea (non-marine)	44	33		65
Insecta	210	237		631
Collembola	> 30	60		41
Araneida	20	19		60
Acarina (free-living)	140	127		127
Myriapoda	3	0		1
Mammalia	0	3	2	8
Aves	0	17	6	39
Flowering plants	0	164	57	515
Bryophytes	26	373	150	612
Lichens	150	597	> 100	950

[1] Data sources: Svalbard – Barr (1995), Elvebakk & Hertel (1996), Frisvoll & Elvebakk (1996), Rønning (1996), Coulson & Resfeth (2004), Coulson (2007); Franz Josef Land – Barr (1995); Greenland – Jensen & Christensen (2003); sub-Antarctic – Convey (2007a).

TABLE 5
The recorded occurrence of alien non-indigenous species across Antarctic biogeographical zones[1]

	Continental Antarctic	Maritime Antarctic	Entire sub-Antarctic	South Georgia	Marion	Prince Edward	Crozet	Kerguelen	Heard	Mac Donald	Macquarie
Dicotyledons	0	0	62	17	6	2	40	34	0	0	2
Monocotyledons	1	2	45	15	7	1	18	34	1	0	1
Pteridophytes	0	0	1	1	0	0	1	1	0	0	0
Total non-indigenous plants	0	2	108	33	13	3	59	69	1	0	3
Invertebrates	0	2–5	72	12	18	1	14	30	3	0	28
Vertebrates	0	0	16	3	1	0	6	12	0	0	6

[1] Extracted from Frenot *et al.* (2005) and Convey (2007b); see also Greenslade (2006) for a detailed description of established and transient alien species, and species recorded only synanthropically, from sub-Antarctic Macquarie Island.

Sub-Antarctic floras and faunas are typically disharmonic and do not include representatives of several taxonomic and functional groups common in lower latitudes. Sub-Antarctic plant communities do not include woody plants, and are dominated by herbs, graminoids and cushion plants. These floras also generally do not include species requiring insect pollination, other than possibly two little-known endemic orchid species from Macquarie Island, and pollinating insects likewise do not form a component of the insect faunas (Convey *et al.* 2006a). Megaherbs are a striking element of the flora of many islands, being an important structuring force within habitats, and a major contributor of biomass (Meurk *et al.* 1994a, Mitchell *et al.* 1999, Fell 2002, Shaw 2005, Convey *et al.* 2006a). Several different plant families are represented by regional and endemic megaherb taxa (Apiaceae – *Stilbocarpa*, Brassicaceae – *Pringlea*, Asteraceae – *Pleurophyllum*). Large tussock grass species (Poaceae – *Poa* and *Parodiochloa*) also provide a dominant structural presence. These plant growth forms present an unusual combination of morphological and life history characteristics (Convey *et al.* 2006a), that includes high primary production and biomass allocation to both leaf and underground storage tissue, seed mass and seed output. Their dominance on sub-Antarctic islands is thought to have been encouraged by the absence of natural vertebrate herbivores (Meurk *et al.* 1994a, Mitchell *et al.* 1999), while also having other adaptive benefits relating to the harvesting and focusing of low light levels and aerosol nutrients (Wardle 1991, Meurk *et al.* 1994b). The recent anthropogenic introduction of vertebrate herbivores to most sub-Antarctic islands has led to considerable and negative impacts on megaherb-based communities (Frenot *et al.* 2005, 2007, Shaw *et al.* 2005, Convey *et al.* 2006b).

Across the sub-Antarctic there are no native land mammals, reptiles or amphibians and very few non-marine birds. The latter are limited to three species of freshwater duck (two on South Georgia, one on Îles Kerguelen and Crozet), a single passerine endemic on South Georgia (*Anthus antarcticus* Cabanis, 1884 the South Georgia Pipit), and two scavenging sheathbills. Although outside the scope of this review, many of the islands are of considerable conservation importance, hosting globally significant populations of marine vertebrates (Woehler *et al.* 2001). The most abundant macroscopic terrestrial invertebrates of the sub-Antarctic are the micro-arthropod mites and springtails, with population densities in tens to hundreds of thousands of individuals m^{-2}. There are also enchytraeids, earthworms, tardigrades, nematodes, spiders, beetles, flies and moths, with smaller representation of some other insect groups (Gressitt 1970, Convey 2007a). Few of these invertebrates are thought to be true herbivores, with the exception of some beetles and the moths, although detailed autecological studies are typically lacking. Spiders and a small number of carabid, dytiscid and staphylinid beetles are carnivorous but, other than these, macro-invertebrate predators are absent, and predation levels are thought to be insignificant (although this is a generally untested assumption). The introduction of carabids to parts of South Georgia and Îles Kerguelen is leading to extensive changes to local community structure, which threaten the continued existence of some indigenous and/or endemic invertebrates (Ernsting *et al.* 1995, Frenot *et al.* 2005, 2007). Regional warming has also been predicted to rapidly increase the impact of certain indigenous predators, such as the diving beetle *Lancetes angusticollis* (Curtis, 1839) in lakes on South Georgia (Arnold & Convey 1998). Despite the preponderance of detritivores, decay processes are slow in most habitats. Detailed studies on Marion Island have indicated that indigenous detritivorous invertebrates are currently insufficient to overcome a bottleneck in the decomposition cycle (Slabber & Chown 2002).

Although sub-Antarctic ecosystems are more diverse and complex than those of more extreme Antarctic latitudes (Convey 2007a), they remain simple in global terms, commonly lacking or with low diversity in specific taxonomic or biological functional groups. Therefore they are thought to lack the functional redundancy that is typical of more diverse ecosystems. This lack of indigenous diversity raises the possibility of new colonists (natural or anthropogenically-assisted) filling previously unoccupied ecological niches. Such colonists could include new trophic functions or levels, and would inevitably change fundamentally the structure and function of trophic webs. Responses of indigenous biota to such changes and the advent of new competitors and predators will be constrained by their typically "adversity-selected" life history strategies (Convey 1996b), which primarily confer abilities to survive abiotic environmental extremes, while competitive abilities are very poorly developed. These native species and communities appear to be particularly vulnerable to predation from invading taxa, as native invertebrate predators are generally of little or no significance (Ernsting *et al.* 1995, Convey 1996b, 2003, Frenot *et al.* 2005, Convey *et al.* 2006b).

BIOGEOGRAPHIC PATTERNS AND DRIVERS

The widely varying geological and glaciological histories of the sub-Antarctic islands provide the template on which their patterns of biodiversity and biogeography have evolved. Understanding of these patterns relies on resolution of three fundamental problems: (1) many areas have not been systematically explored, even on such defined and small land masses; (2) many of the less charismatic taxa have not received basic survey attention even for those that have, and comprehensive and up-to-date databases of the distributions of sub-Antarctic species do not exist; (3) both robust systematic studies and modern molecular phylogenies are absent for many taxa, while very few taxonomists or funding agencies have resources to devote to the biota of this region. Although a number of recent compilations are available either for specific islands or specific taxonomic groups, both of published records and of newly (re-)examined material (Pugh 1993, Bednarek-Ochyra *et al.* 2000, Øvstedal & Smith 2001, Pugh *et al.* 2002, Pugh & Scott 2002, Seppelt 2004, Chown *et al.* 2006, Greenslade 2006, Ochyra *et al.* in press), these factors mean that any biogeographic assessments inevitably rely on incomplete data and, hence, are constrained to weak approaches to phylogeographic analyses (Chown & Convey 2006, 2007). For instance, the closest relatives of many prominent endemic sub-Antarctic invertebrate taxa (the *Ectemnorhinus*-group weevils and *Pringleophaga* spp. tineid moths) remain unconfirmed except on the basis of conventional systematics (Jeannel 1964, Kuschel & Chown 1995). Using the available data, Chown *et al.* (1998) identified that several well-known biodiversity drivers were important across the Southern Ocean islands, including area, distance from sources, temperature, richness of other biotic groups and human occupancy (see also Selmi & Boulinier 2001).

Perhaps the most fundamental challenge relating to sub-Antarctic terrestrial biogeography is that of separating the two influences of dispersal and vicariance in determining the current distributions across the region. This dichotomy is superimposed on a second area of controversy, that of whether the entire sub-Antarctic region can be regarded as a single biogeographic province (the "Insulantarctic" hypothesis – Udvardy 1987), or whether a "multiregional" hypothesis is more appropriate (i.e., that there are different provinces of the Southern Ocean, with different origins, history and sources of biota – Kuschel & Chown 1995, Craig *et al.* 2003). The debate essentially rests on whether all the islands share enough of their biotas to form a single biogeographic entity (as proposed by Holdgate 1960, Skottsberg 1960, Udvardy 1987, van de Vijver & Beyens 1999), or whether there are sufficient regional differences simply to require that each is most appropriately linked to the Southern Hemisphere continent to which they are closest (Gressitt 1970, Smith 1984, Morrone 1998, Cox 2001, McDowall 2005).

In many respects this is a sterile debate (Chown & Convey 2006), with the conclusion drawn depending to a large extent on the particular taxonomic group under consideration (Greve *et al.* 2005). The latter authors present evidence, based on the degree of nestedness shown in distributions of species and genera of different groups, that illustrates instances of support for both the Insulantarctic and multi-regional hypotheses. Distribution patterns of groups that are weak dispersers are strongly influenced by regional source pools, in particular the most adjacent continents and large islands within archipelagoes (Morrone 1998), whilst those of mobile taxa (i.e., those with dispersing life stages) are more uniform (Barrat & Mougin 1974). A number of very different organisms (oribatid mites – *Halozetes*, springtails – *Cryptopygus*, grass – *Deschampsia*, herb – *Acaena*) share circum-sub-Antarctic distributions (Bergstrom *et al.* 2006; illustrated in fig. 1 for *Acaena*), which are most parsimoniously explained by dispersal processes acting across the entire region. However, there remain important anomalies. For instance, bryophytes are widely regarded as efficient dispersers, producing a range of spores and other propagules (Longton 1988). Of the terrestrial biota of the Antarctic continent bryophytes are the only major group present to show the very low levels of species endemism that should be associated with the widely assumed pattern of recent (post-Pleistocene glaciation) colonisation (Chown & Convey 2006, Peat *et al.* 2007, Convey *et al.* in press b). However, while Muñoz *et al.* (2004) proposed that sub-Antarctic bryophyte distribution patterns support an hypothesis of dispersal by wind across the region, nestedness analysis suggested little difference was present in reality between them and what are highly

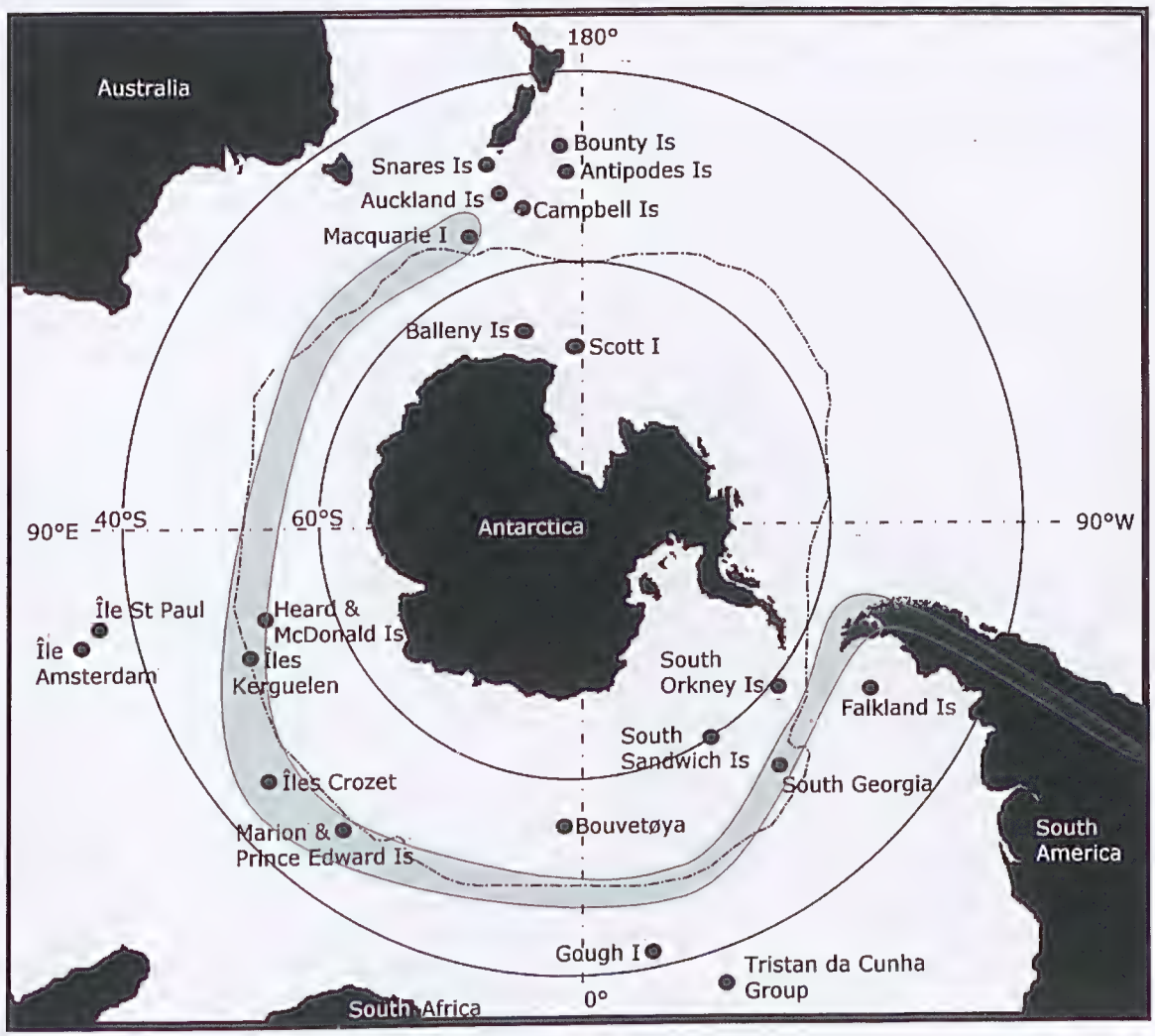

FIG. 1 — The circum-Antarctic distribution of the herb Acaena *(reproduced from Bergstrom* et al. *2006).*

regionalised vascular plant distributions (Greve *et al.* 2005). This contradiction may relate in part to the use of imperfect taxonomy in the earlier study, but it may also illustrate that long-range bryophyte dispersal may not be as effective as is commonly assumed.

While the majority of islands are too young to carry a signal of their biological history on a Gondwana-breakup timescale, the older islands of South Georgia and Kerguelen have the potential to do so. However, terrestrial fossil evidence is generally sparse in the sub-Antarctic, other than fossil floras that are known from islands of the Kerguelen Plateau (Chastain 1958, Quilty & Wheller 2000; Truswell *et al.* 2005) and a single example of fossil wood, dating from the Early Cretaceous, from South Georgia (Gordon 1930). Nothing can be concluded about continuity between fossil and contemporary biota. Other studies have inferred signals of ancient regional origin from contemporary distributions (Brundin 1966, Darlington 1970, McInnes & Pugh 1998, Craig 2003). An example of this is provided by the Collembola genus *Setanodosa*, known only from South Georgia in the Antarctic/sub-Antarctic region, and from South America, South Africa and Australia. The implication is of a Gondwanan distributional link, at least between the major continents, although in the absence of molecular phylogenetic studies it is not currently possible to differentiate between this and more recent dispersal in explaining the presence on South Georgia.

A single molecular phylogenetic study of Scotia Arc Diptera has proposed the continuous presence of an evolutionary lineage of chironomid midge on the South Georgian microplate over a timescale dating from its separation from southern South America and the Antarctic Peninsula (Allegrucci *et al.* 2006), 40–50 ma. Also based on molecular phylogenetic analyses, Stevens *et al.* (2006) inferred recent (<2 ma) dispersal/colonisation events of springtail (*Cryptopygus*) species between some sub-Antarctic islands, with a close association between estimated times of divergences based on a molecular clock and proposed geological ages of islands. On a more recent timescale, local isolation of populations by Pleistocene glacial cycles has been an important evolutionary force driving differentiation processes (Marshall & Convey 2004, Mortimer & Jansen van Vuuren 2007). These studies demonstrate the potential for the application of such techniques to shed light on the biogeographical history and structure of the sub-Antarctic, and rapid advances are now being made in this field.

Ignoring for the moment the direct influence of humans, there are three broad mechanisms that might facilitate natural colonisation and dispersal processes into and within the Antarctic (Gressitt 1970, Hughes *et al.* 2006). These are transport in air, water or via a third-party vector (other organisms, debris). Wind is well known to play a major role in the colonisation of isolated environments by smaller organisms, particularly those with an appropriate stress-resistant life stage. In a sub-Antarctic and Antarctic context, this applies to bryophytes, lichens, many microbes and certain invertebrates such as rotifers, tardigrades and some freshwater crustaceans and terrestrial arthropods (Laybourn-Parry & Marchant 1992, Marshall 1996, Muñoz *et al.* 2004, Greve *et al.* 2005). However, it is also currently thought that long-distance aerial dispersal is inappropriate for other elements of the sub-Antarctic and Antarctic faunas, such as most terrestrial arthropods and molluscs (Pugh & Scott 2002, Pugh 2003), while it may only operate on relatively short scales of distance for others such as Collembola (Hawes *et al.* 2007b). Other than the study of Marshall (1996), which relates to a maritime Antarctic island location, there are no recent studies quantifying the frequency or magnitude of aerobiological transfer into the Antarctic region. However, it is clear from the occasional arrivals of known migratory moth species that aerial transfer to the sub-Antarctic islands does occur (Greenslade *et al.* 1999, Convey 2005).

Given the scale of physical isolation of the sub-Antarctic islands, and the typical meteorological conditions and sea states experienced at their latitudes in the Southern Ocean, transport in water or on the water surface would seem unlikely, and there are no confirmed instances. However, some groups well-represented in sub-Antarctic terrestrial faunas, such as the ameronothroid mites and some isotomid and hypogastrurid springtails, are known to show very wide ecophysiological tolerances and can survive long periods in or on the surface of seawater (Strong 1967, King *et al.* 1990, Davenport & MacAlister 1996, Coulson *et al.* 2002, Marshall & Convey 2004, Hawes *et al.* 2007a). This mechanism is likely to underlie dispersal of marine littoral species, some of which also then occupy supralittoral habitats. There are also no demonstrations of transfer of terrestrial species into or within the Antarctic region on floating debris, although the possibility has been recognised and examples relating to marine biota exist (Barnes & Fraser 2003, Hughes *et al.* 2006).

Finally, the potential route of zoochory (transport attached to other animals, usually vertebrates) has been recognised (Pugh 1997) although, again, there are few confirmed examples of this occurring in the Antarctic or sub-Antarctic. Earlier reports are limited to algae and microbiota (Gressitt 1964, Schlichting *et al.* 1978). Recently, Krivolutsky *et al.* (2004) have carried out a more detailed study of the arthropod load carried by a range of Antarctic bird species collected on the South Shetland Islands and Antarctic continent. They report several species of mite and a single spider being collected from the plumage of these birds, none of which were apparently species resident at the collection locations. Perhaps most surprisingly, species thought to be terrestrial were collected from the plumage of penguins, including from Emperor Penguins that do not come into direct contact with terrestrial habitats at any point in their life-cycle. In a sub-Antarctic context, the most plausible bird vector species are those that routinely migrate to other continents (skuas, gulls and sheathbills) (Barnes *et al.* 2006). In some cases, some invertebrates and plant and microbial propagules may possess appropriate resistance features to permit survival of passage through vertebrate guts (Frenot *et al.* 2005), such as those of seals (Pugh 1994) and sub-Antarctic ducks (T. Martin, pers. comm.).

HUMAN IMPACTS

Antarctica and the isolated lands of the Southern Ocean are unique in never having had an indigenous human population or a long-term history of human residence and impact. The short human history in the region commenced with early exploring voyages into the Southern Ocean, and with the discoveries of the isolated peri-Antarctic islands, within the past two to three centuries. The Antarctic Peninsula (West Antarctica) was first sighted in 1820, and probably landed on in 1821, and humans first set foot on East Antarctica in 1895 (Headland 1989). Direct human impacts so far have largely been restricted to Southern Ocean marine ecosystems

(sealing, whaling, fishing) and sub-Antarctic terrestrial ecosystems (Knox 1994, Frenot *et al.* 2005, 2007, Convey *et al.* 2006b, in press a). Indirectly, human activities are also impacting the Antarctic through the pervasive presence of persistent organic and inorganic pollutants (Bargagli 2005), and the processes of climatic change consequential on global warming and stratospheric ozone depletion (Walther *et al.* 2002, Convey 2003, 2006). Human contact with Antarctica is currently growing rapidly (Navareen *et al.* 2001, Frenot *et al.* 2005, COMNAP 2006, IAATO 2006). Identifying and responding to the requirements for conservation of Antarctic ecosystems are high profile issues both within the Committee for Environmental Protection of the Antarctic Treaty System, and within the sphere of public interest generated through the media and activities of non-governmental organisations.

Parts of the Antarctic region are currently experiencing rapid change in a number of climatic variables – most obviously temperature, but also in precipitation patterns and amounts, and cloudiness. Some of the most rapid temperature increases seen worldwide over the past 50 years have been documented along the western Antarctic Peninsula and associated Scotia Arc archipelagoes (King *et al.* 2003, Vaughan *et al.* 2003, Turner *et al.* 2005). Although the only sub-Antarctic island included in this region is South Georgia, the maritime Antarctic island archipelagoes are also included; some authors group these with the more strictly defined sub-Antarctic islands. Warming trends have also been identified at several other sub-Antarctic locations (Jacka & Budd 1998, Marion Island - Smith & Steenkamp (1990), Smith (2002), Îles Kerguelen - Frenot *et al.* (1997), Macquarie Island - Tweedie & Bergstrom (2000)). At finer, seasonal, timescales as yet there are no consistent seasonal patterns across the sub-Antarctic islands. Thus, Macquarie Island appears to be warming most during late summer and early autumn (Adamson *et al.* 1988), although this was not confirmed by Tweedie & Bergstrom (2000). Highest warming rates are seen on Marion Island during late winter and early summer (Smith & Steenkamp 1990). There is some evidence that Îles Kerguelen are warming more in summer (Allison & Keage 1986; but see also Frenot *et al.* 1997 who reported no seasonal difference in a longer dataset). Precipitation patterns are also changing on some islands, with reports of both increases on Macquarie Island (C. Tweedie, D. Doley & D. Bergstrom unpublished data), and decreases on Marion Island and Îles Kerguelen (Smith & Steenkamp 1990, Frenot *et al.* 1997, Chown & Smith 1993, Smith 2002, Chapuis *et al.* 2004). In concert with these changes, rapid rates of glacial retreat have taken place on the heavily glaciated South Georgia and Heard Island (Gordon & Timmis 1992, Pugh & Davenport 1997, Kiernan & McConnell 2002). This process has various consequences, including exposing new ground for colonisation, altering (generally increasing) water input to terrestrial habitats, and opening up overland routes for movement of terrestrial biota into previously isolated regions. The latter is of particular significance for South Georgia, as it permits the movement of introduced rats and reindeer into new areas, with highly deleterious consequences for native ecosystems (Frenot *et al.* 2005, Convey *et al.* 2006b).

The consequences of changes in two major environmental variables (temperature, water availability) have formed a particular focus in studies of climate change responses in the Antarctic, although few such studies have focused specifically on the sub-Antarctic islands. The widely reported warming trends have led to a range of general predictions (Convey 2003), including increases in the rates of colonisation on both local and long-distance scales, increased terrestrial diversity and biomass, and increased trophic complexity (through the inclusion or greater functional representation of higher trophic levels). As yet, few studies have addressed these processes in a sub-Antarctic context, although environmental manipulation studies on South Georgia (Smith 2001) have demonstrated local colonisation and community development potential through dormant propagule banks. Negative consequences from environmental changes are also clearly possible, and one such might be a reduction in local extent of *Azorella* cushion plants on Marion Island, influenced by the trend of reduced precipitation recorded on this island (le Roux *et al.* 2005).

Human contact with the sub-Antarctic over the past two centuries or so has led to the introduction of over 200 known non-indigenous species (table 5; Frenot *et al.* 2005). The majority of these are vertebrates or flowering plants, although an increasing number of invertebrates are now being recognised (Greenslade 2006). However, it remains the case that the quality of data available varies widely between the sub-Antarctic islands and also between the major higher taxonomic groups. Thus, while the presence of non-indigenous flowering plants is quite well known throughout the region, little or no attention has been given to bryophytes or lichens. Likewise, detailed data are unavailable for most microarthropod and other microfaunal groups (nematodes, tardigrades, rotifers), to the extent that even authoritative lists of indigenous species are not available in many cases, rendering the identification of non-indigenous species problematic (although see Greenslade (2006) for Macquarie Island). However, it is clear that some major sub-Antarctic islands remain relatively unaffected by the establishment of non-indigenous species (particularly Prince Edward and Heard islands). The value and conservation status of these two islands has been recognised by, in the former case, the operation of a detailed and proscriptive management plan (Anonymous 1996), and in the latter by the awarding of World Heritage Site status (see Chown *et al.* 2001). However, other sub-Antarctic islands have been and continue to be heavily impacted (particularly South Georgia, Îles Kerguelen, Macquarie Island). On these islands there have been well-documented examples of drastic ecosystem impacts, mainly relating to rodent or cat predation of indigenous birds, mammalian grazing, and the spread of cosmopolitan weed plant species (see Frenot *et al.* (2005) for review). Because some of the impacted species and ecosystems are very restricted globally, damage to these islands presents an important threat to regional and global biodiversity. Although natural colonisation of the species-poor sub-Antarctic ecosystems is an ongoing process, the importance of anthropogenic activity in facilitating introduction and establishment must also be recognised. Studies on sub-Antarctic Marion Island and South Atlantic Gough Island suggest that the frequency of anthropogenic introduction outweighs that of natural processes by up to two orders of magnitude or more (Gaston *et al.* 2003, Gremmen & Smith 2004, Pugh 2004). After only two centuries of contact, anthropogenic introductions now account for over 50% of angiosperm biodiversity on South Georgia and Îles Kerguelen. Non-indigenous species that become invasive are now presenting major challenges for ecosystem management, and in most cases no simple solutions are available. Even in cases where eradication of introduced species is practicable (most obviously, grazing

large mammals and cats), it is not clear that eradication will simply lead to ecosystem recovery.

CONCLUSIONS

A number of formulations or definitions of the sub-Antarctic are in more or less common use in the literature. The definition used in the current paper, based on climatic similarities and the common absence of woody plants, identifies a discrete set of isolated Southern Ocean islands at latitudes of c. 47°S to 54°S, all lying relatively close to the oceanic PFZ. Terrestrial ecosystems on the majority of these islands are plainly post-Gondwanan in origin, as most islands formed long after Gondwana-breakup. A few (particularly South Georgia) provide evidence of ancient biogeographical signals consistent with events during the final breakup of Gondwana. The extreme isolation and generally poor environmental conditions experienced in this region are indicated by the overall low levels of biodiversity present on all islands, and their disharmonic taxonomic composition. Contemporary biogeographical patterns vary between groups of biota or habitats, with examples supporting both Insulantarctic and multi-regional hypotheses for their origin, and strong indications of both the importance of wind and other means of long-distance dispersal as well as of more local evolutionary radiation. Recent human impacts (climate change, introduced species) are already strong, and may far outweigh natural dispersal processes, presenting major management and conservation challenges.

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SHORE ECOLOGY IN THE SUB-ANTARCTIC

by Rod Simpson

(with two tables)

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Research on the shores in the sub-Antarctic region is discussed with respect to how lines of investigation developed, current status, and what areas of research should attract priority in relation to both outstanding questions and concerns for the ecological well-being of the region. The remoteness of the sub-Antarctic requires coordination of effort and resources and it is suggested that greater advances could be made if there is international coordination in a more prescribed way.

Key Words: sub-Antarctic, shore ecology.

INTRODUCTION

The following is not intended as an exhaustive review of the works that have been conducted on the biota and ecology of the seashores of the sub-Antarctic region; rather, it concentrates on the type of work that has been done and what directions might be the more gainful for future research, taking into account the status of the research so far, the features of the region and current global concerns.

Shore ecology is used here to refer to the marine benthic biota of the littoral and sublittoral areas. The seashores support other animals. Penguins and seals use the seashore for segments of their life-cycles, particularly breeding, but the ecology of these animals is treated by researchers of these groups in other parts of these proceedings.

THE REGION AND THE ISLANDS

The nature of the region and the location and sizes of the islands within the region are identified by Selkirk (2007) and Quilty (2007). Seashore ecology is influenced by a number of factors. The islands are scattered across a virtually unimpeded oceanic region with a "west wind drift" as a dominating near-surface influence. The positions of the Antarctic Convergence and the sub-Antarctic Polar Frontal Zone have a strong influence. The harsh yet seasonally equable weather in many regions, the difficulty of access for study, and the influence of the current global increases in sea water temperature are all important factors.

CURRENT STATUS OF RESEARCH

In 1988, I reviewed studies of sub-Antarctic shores, with particular reference to Macquarie Island (Simpson 1988). That publication outlines the beginnings of research in the region, leading to a statement on the status of research at that time. The present status of research shows advances in some areas. In summary, the first research involved collections during early expeditions and the first years of occupancy of sub-Antarctic bases. Taxonomic studies allowed the first evaluations of the biogeographical affinities across the islands, to temperate regions to the north, and to the Antarctic in the south. Descriptive ecology followed, centred on the distributions of biota in the littoral and sublittoral and how those distributions related to the contemporary concepts of zonation (see Simpson 1988). More specific ecological studies examined causes influencing the distribution of biota, such as physiological tolerances, predation and competition, including comparisons with work in temperate regions where similarities and differences were drawn. A further area of research that has received considerable attention is the reproduction of marine invertebrates. The harsh climatic conditions and the geographic isolation of scattered sub-Antarctic islands provides a fertile ground for linking reproductive modes with ecological and distributional extremes (see Simpson 1988).

What has happened since 1988? Research into previously studied areas has continued and some new ones opened up. Tables 1 and 2 are compiled from a survey of 65 publications up to 2006 that deal with shore biota and ecology across the more studied locations from the sub-Antarctic region. Table 1 shows the research topics undertaken at these locations and table 2 ranks the frequency with which these topics are covered within the publications surveyed. In some cases, more than one topic or location are entered from the one publication. Further subdivision into more topics would be possible (e.g., algae, echinoderms). More exhaustive searching may alter the middle rankings slightly but the two tables give a good indication of the research attention to shore biota and ecology in the sub-Antarctic. There is little doubt that taxonomy would remain first in frequency of publication output as the survey did not include all the initial taxonomic papers that examined specimens collected during the early expeditions. It is not the intention here to provide a list of references behind these tables or to provide commentary on the merits of the works across such a wide spectrum. Researchers would need to conduct their own searches in specific areas of interest.

CURRENT AND FUTURE PRIORITIES IN RESEARCH

What should be the priorities for future research work in the sub-Antarctic? These must be weighed against the difficulties and constraints in logistics, financial support and time, in getting to this remote region of the world.

Taxonomic work should continue wherever and whenever those with the expertise can provide time to work on material from the sub-Antarctic. By providing more definitive

TABLE 1
Topics of investigation across the sub-Antarctic

	Macquarie	Kerguelens	Sth Georgia	Marion and Prince Edward	Heard	Crozets	South America to Antarctic Peninsula	Circum sub-Antarctic
Taxonomy	x	x	x	x	x	x	x	x
Biogeography and distribution	x	x	x	x			x	x
Littoral algae	x		x	x	x		x	
Littoral fauna and ecology	x	x	x	x	x		x	
Molluscan ecology	x	x	x	x			x	
Reproduction	x	x					x	
Beach fauna			x					
Physiological	x	x	x				x	
Biochemistry		x						
Community Structure	x						x	
Pollution	x						x	
Sublittoral	x		x				x	
Monitoring for species introductions	x						x	

TABLE 2
Ranking of frequency of topics investigated

Rank	Frequency (from 65 publications)	Topic
1	25	Taxonomy, including biogeographical inferences
2	16	Littoral ecology (flora and fauna)
3	12	Reproductive ecology
4	11	Molluscan ecology
5	6	Community structure, population dynamics
5	6	Physiology and biochemistry
7	5	Pollution ecology
8	4	Sublittoral ecology
8	4	Mechanisms of distribution
10	2	Monitoring for introduction of species
11	1	Beaches

phylogenetic relationships for the biota of the region, distributional pathways of the past and of the future can be better understood. The project on the Census of Marine Life is a significant step towards this goal. However, as O'Hara (1998a) pointed out in examining the echinoderms of Macquarie Island, the nature of the Southern Ocean and the breakup of Gondwana are likely to have promoted polymorphism in isolated species complexes. This presents problems not only for taxonomy but also for attempts to trace origins and past and present distributional pathways.

Molecular taxonomic methods will be useful in consolidating the strength or otherwise of relationships among sub-Antarctic biota. This should be a priority research area because understanding the geographic origins of the biota, coupled with knowledge of distributional and recruitment pathways, will assist in determining measures (where possible and/or deemed necessary) to meet changes induced by human activities, either those that have a direct impact or those that have an indirect effect such as that from global climate changes.

A dramatic event occurred when the supply ship M.V. *Nella Dan* ran aground at Macquarie Island in December 1987, spilling marine diesel onto the shoreline. This unfortunate event provided a springboard for pollution studies on sub-Antarctic shores, not only for the immediate effects but also for understanding the degree of persistence of pollution in these waters (Pople *et al.* 1990, Simpson *et al.* 1995, Smith & Simpson 1995, Smith & Simpson 1998). With more frequent human visitation and use in these areas, a means of monitoring any disturbance against knowledge of a previous background is required. The shoreline is an area that can provide a laboratory of organisms that signal change in marine conditions. Smith & Simpson (1995) showed that the fauna of holdfasts of the giant kelp *Durvillaea antarctica* (Chamisso) show considerable promise in this regard. These holdfasts support a high diversity of

fauna at the interface of the shore and the sea, provide a natural and discrete sampling unit, represent a habitat across the entire region, and the faunal community within the holdfasts reflects both natural gradients and disturbance from pollution (such as oiling).

Concomitant with concerns about pollution disturbance is the possible introduction of alien species, particularly via shipping and human visitation. Species extensions through their own distributional capabilities in response to climate change will be such large and widespread events that little can be done, except to remedy the root cause itself, such as global warming. The laissez faire approach would be to say that, in the case of global warming for instance, it is insignificant in comparison to the long-term natural cycles of the planet. There is even a more controversial view, that the more direct influence of humans is a "new evolution" for the planet, so live with it. I don't think we can or should take such chances. Thus, monitoring for species introductions should also be a priority research area.

Understanding recruitment and reproductive interchange within and across invertebrate populations in the sub-Antarctic is a foremost step for evaluating the causes and possible remedies for adverse disturbances, whatever the sources. Research into these questions forms another priority.

One area that requires confirmation is the long-held view that kelp-rafting by fauna is a vector for dispersal of marine invertebrates across the Southern Ocean. If this is so, it could provide a mechanism for dispersal of exotic species. Smith (2002) revealed the potential for such a dispersal mechanism in calculations from a shipboard observation program that indicated 70 million rafts of *Durvillaea antarctica* afloat at any one time between the latitudes of 46–53°S. Further, 20 million of these could have a holdfast attached, and this holdfast provides an extra haven for a diversity of fauna. Survival of invertebrates would need to be verified. Helmuth *et al.* (1994) showed that the brooding bivalve, *Gaimardia trapesina* (Lamarck, 1819), was capable of long-term survival on kelp rafts as shown from collections of kelp rafts approaching the shores of South Georgia. O'Hara (1998b) cautioned that dispersal by the West Wind Drift could be overstated and that both separation processes and shelf/slope migrations along submarine ridges and plateaux have played a significant role in determining the faunal composition and distributions across the Southern Ocean. Again, molecular techniques to define the ancient and recent affinities among populations would greatly assist in providing answers to these questions.

COORDINATION OF RESEARCH

The above priorities need not be the only research undertaken. All areas of research must allow for the topics of discovery that add to knowledge with as yet unforeseen outcomes. The extra logistic requirements and difficulties for work in the sub-Antarctic region prompt a coordinated effort to ensure the best uses of available funds and support structures. Ideally, an international approach would greatly assist in that a central body could call for research proposals with indications of favoured themes. Allowing this body to control the funding from different countries would be difficult to implement but the sub-Antarctic, an international area, almost demands such an approach. Whatever the decision process and whoever the decision makers, attention to selection of supported research will become more critical with threats of change with uncertain consequences.

The questions are obvious and have been addressed in the programs of some countries across all fields of study, such as: how to best coordinate the logistical and funding support; the balance between contracted versus discovery research; is research into disturbance and management the top priority?; offshore vs. onshore; and what are the organisms and/or populations to study?

The need and the opportunity are both there to give greater attention to these questions, hopefully at the level of international coordination.

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TERRESTRIAL ECOLOGICAL PROCESSES AND PROBLEMS ON SUB-ANTARCTIC ISLANDS

by Valdon R. Smith

(with three text-figures and one table)

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On the basis of their vegetation and soils, sub-Antarctic island ecosystems are considered to be part of the tundra biome. However, sub-Antarctic island vegetation is more productive and nutrient cycling more rapid than in Northern Hemisphere tundra. Human occupation and exploitation on the islands has comprised mainly sealing, whaling and, in some instances, fishing and agriculture. Research stations have also been established for meteorological monitoring and scientific research. All these activities have affected the islands' floras and faunas but the greatest impact of humans has been through the introduction of alien organisms. Because the islands' indigenous biotas are species-poor and lack cardinal trophic groups that are common in other ecosystems (especially mammalian herbivores and predators), an introduced species that becomes invasive on an island can have insidious, but far-reaching, effects on ecosystem functioning. Such effects are the focus of this paper and the principal examples given are the effects of the introduced house mouse and a European slug on nutrient cycling at Marion Island. Manuring by seabirds and seals is also an important determinant of ecosystem structure and function at sub-Antarctic islands. Introduced domestic cats have reduced burrowing bird populations on some of the islands, and at Marion Island the populations of most surface-nesting birds have also declined, probably due to human exploitation of their oceanic food resources. This has far-reaching implications for ecosystem functioning. The sub-Antarctic region is also becoming warmer; at some islands this is coupled with decreased, and at others with increased, precipitation. Some implications of these climatic changes for ecological functioning are presented. The most important is that a warming climate will increase the probability of introduced organisms becoming established on an island. This, together with increasing human visitation and occupancy (the major cause of species introductions), implies that it is inevitable that the rate of establishment of invasive biota on the sub-Antarctic islands will increase.

Key Words: Sub-Antarctic islands, alien biota, climate change, ecosystem functioning, primary production, nutrient cycling, island ecology.

INTRODUCTION

Most oceanographers define the sub-Antarctic region as the zone between the Antarctic and Subtropical Convergences in the Southern Ocean. The latitudinal distribution of many marine organisms is limited by these boundaries, but this is less true of sub-Antarctic terrestrial organisms such as plants (Wace 1965), insects (Gressitt 1970), spiders (Pugh 2004) and avifauna (Barrat & Mougin 1974). Hence, terrestrial biologists have tended to delimit the sub-Antarctic region on the basis of plant physiognomic, plant biogeographic, vegetation structure or climatic criteria. Lewis Smith (1984) used these criteria, especially those related to vegetation (Wace 1965) and climate (Holdgate 1964), to produce a regional classification of Antarctica and the Southern Ocean. This recognises six islands or island groups as belonging to the sub-Antarctic region (South Georgia, Macquarie Island, Marion and Prince Edward islands, Îles Crozet, Îles Kerguelen, Heard and McDonald islands), all situated within a few degrees latitude north or south of the Antarctic Convergence. Because of the cold Bouvet Current from the Weddell Sea the Convergence extends farther north in the Indian Ocean so that relatively low-latitude islands such as Marion, Prince Edward and Îles Crozet are within this sub-Antarctic zone, even though they are farther north than the islands of the New Zealand continental shelf (Campbell, Antipodes, Auckland, Snares). These latter, because they possess a well-developed shrub and/or low tree vegetation, are considered to belong to the cool temperate zone, together with the Tristan da Cunha-Gough Island group, Île Amsterdam, Île Saint-Paul, Falkland Islands and southern Tierra del Fuego. At the other extreme, Bouvetøya, the South Sandwich Islands, South Orkney Islands and South Shetland Islands are considered to be in the maritime Antarctic zone.

This paper deals with ecological processes and problems on those islands considered as sub-Antarctic *sensu* Lewis Smith (1984). The ecological problems are mostly related to human activities, although the sub-Antarctic is also experiencing a more rapid rate of climate change than most other parts of the world, and this is also affecting the islands' ecosystems. Humans have long impacted on the biota and ecology of sub-Antarctic islands, in the eighteenth and nineteenth centuries through sealing and whaling and later through the establishment of meteorological and research stations. There also has been some agricultural activity, mainly on Îles Kerguelen. In most instances, the human footprint caused by these exploitative activities has been small but on some islands it has been more significant. For instance, between 1904 and 1965 South Georgia was the most industrialised and densely populated place (up to 2000 human inhabitants) south of the Antarctic Convergence, connected with sealing and whaling, and leading to large engineering works, massive local industrial pollution and acute and chronic oil spillages (Headland 1984). The two phases of human exploitation of the sub-Antarctic islands (whaling/sealing and research) and their effects are discussed by Frenot *et al.* (2005) and Convey *et al.* (2006), who also consider a third phase of human exploitation – the burgeoning Antarctic tourism industry. The details presented by those authors are not repeated here; rather, discussion concentrates on the effects that humans have had, and are likely to continue to have, on ecosystem functioning at sub-Antarctic islands through the intentional

or inadvertent introduction of alien organisms and also by over-exploiting the surrounding marine ecosystem, which leads to declining seabird populations on the islands. How climatic change might interact with these human-mediated impacts on ecosystem functioning at the islands is also considered.

If an introduced organism becomes invasive on a remote island, its impact is likely to be much more difficult to mitigate or reverse than any effect caused by harvesting the natural populations, anthropogenic pollution or changing the type of land use at that island. To elucidate the effects of alien organisms on ecological fuctioning at sub-Antarctic islands it is necessary to consider to which of the world's ecosystem types the islands belong or most closely resemble, to highlight some important aspects of their terrestrial biotas and to examine what is known about ecological processes such as primary production, decomposition and nutrient cycling at the islands.

The terrestrial sub-Antarctic biome

A useful concept for categorising ecosystems is the "biome", a kind of "subcontinental biotic supercommunity" (Rutherford *et al.* 2006) or "large-scale ecosystem" (Cox & Moore 2000). The concept recognises the role of macroclimate in shaping both the structural and functional properties of the ecosystem at the plant, animal and microbial levels but, because of the dominant nature of vegetation cover, biomes have been delimited mainly on vegetation criteria. On that basis, sub-Antarctic island vegetation has traditionally been considered to be *tundra* or, at least, *tundra-like* (Rosswall & Heal 1975), since it shows strong physiognomic similarities to Northern Hemisphere tundra vegetation (low-growing, dominated by cryptogams, cushion plants, small shrubs, herbs and graminoids, mostly occurring on wet organic soils or peats), although few taxonomic affinities exist between the floras of the two regions. Two sub-Antarctic islands (Macquarie Island and South Georgia) were included in the International Biological Program's Tundra Biome Project (1967–74) and Macquarie Island is part of the International Tundra Experiment.

French & Smith (1985) compared sub-Antarctic and maritime Antarctic terrestrial communities with Northern Hemisphere tundra (ranging from high Arctic polar deserts to temperate alpine tundra) using multivariate analyses of climatic, soil and vegetation parameters. This comparison showed that sub-Antarctic islands possess almost the full range of vegetation types found in Northern Hemisphere tundra (fig. 1), with the sub-Antarctic communities linked to their Northern Hemisphere counterparts at higher latitudes, due to the thermal influence of the Antarctic continent, climatic wetness and wind-chill. In effect, the vegetation of the sub-Antarctic islands resembles that of much higher latitudes (as much as 20 or even 30 degrees higher) in the Northern Hemisphere. More information on the structural and functional similarities and differences between sub-Antarctic island ecosystems and Northern Hemisphere tundra is provided by Smith & Mucina (2006).

Indigenous biota of sub-Antarctic islands

All the sub-Antarctic islands are extremely remote (mostly > 2000 km from the nearest continent). Their indigenous terrestrial biotas (plants and non-marine-based animals)

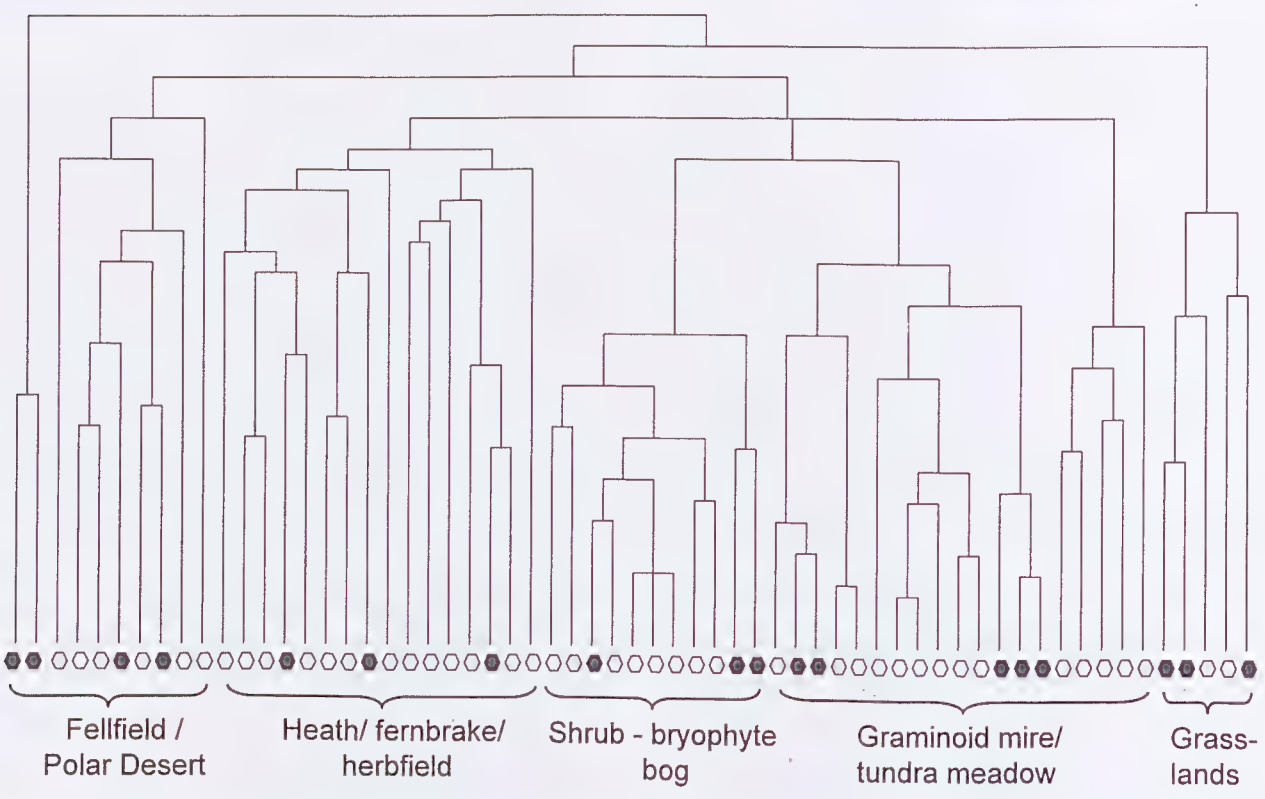

FIG. 1 – Euclidean-distance clustering of Northern Hemisphere tundra plant communities (open circles) and sub-Antarctic island plant communities (closed circles), based on their scores on the first four axes derived from a Principal Components Analysis of plant life-form, soil and climate parameters. Modified from French & Smith (1985).

have been established by the slow process of immigration and colonisation over large expanses of ocean. Consequently this has resulted in a low species diversity. For instance, Lewis Smith (1984) listed 72 vascular plant species indigenous to the whole sub-Antarctic region, whereas the Canadian Arctic Archipelago, a climatically far more extreme region and about 25° of latitude nearer the Pole than the sub-Antarctic, has more than 340 indigenous vascular plant species (Porsild 1964). About 10% of the 72 vascular species on sub-Antarctic islands are endemic to the sub-Antarctic region but only four species are endemic to a single island or island group. This low degree of endemism in the vascular floras of the sub-Antarctic islands reflects the short period of time that speciation could occur. Most of the islands are geologically young – only three (South Georgia, Îles Kerguelen and Heard Island) are substantially older than 10 million years and these were totally, or almost totally, glaciated during the Last Glacial Maximum period 12–27 kyr ago (Chown *et al.* 1998, Sachs & Anderson 2005).

This paucity in species extends to other components of the islands' biotas. There are no indigenous land mammals or freshwater fish, and no island has more than three indigenous land bird species. The insect faunas are small; no island has more than 44 indigenous insect species. Of particular relevance to ecosystem functioning is that important trophic groups are absent, most notably vertebrate herbivores and predators. Even insect herbivores are poorly represented in the indigenous faunas; most insect species on the islands are detritivores. The low biodiversity of sub-Antarctic islands, together with the fact that their native species evolved in isolation, and mostly in the absence of competition or predation, has important implications regarding the susceptibility of ecosystem structure and function to human-introduced organisms.

Alien biota of sub-Antarctic islands

Human-introduced organisms form a significant component of the biota of sub-Antarctic islands. For instance, 108 alien vascular plant species have been recorded in the sub-Antarctic (Frenot *et al.* 2005), 50% more than the number of indigenous species. Eight land mammal species have been introduced and become established on sub-Antarctic islands (Bonner 1984). Several salmonid fish species have been introduced to Îles Kerguelen and Îles Crozet (Davaine & Beall 1997). Knowledge of alien terrestrial invertebrate taxa in the sub-Antarctic is incomplete, but 46% of the insect species (Chown *et al.* 1998) and 38% of the springtail species (Gabriel *et al.* 2001) on Marion Island are introductions. Other introduced invertebrates on sub-Antarctic islands include enchytraeids, earthworms, mites, slugs, spiders, woodlice and a landhopper.

Invasive organisms represent a major threat to sub-Antarctic island biota and ecosystems and have been the topic of several reviews in the past decade. Chown *et al.* (1998) correlated biodiversity and invasive organism successes at Southern Ocean islands (sub-Antarctic and cool temperate zone islands) with abiotic parameters such as temperature, island age, size and altitude, distance to the nearest continent, extent of past glaciation and human occupancy. They showed that island area and temperature explained a high proportion of the variance in species richness in plants, insects and mammals – larger, warmer islands tend to have more species than smaller, colder ones. Human occupancy (numbers of humans on the island) was also important, but the relationship is confused by the fact that larger islands tend to have more humans. The same data as used by Chown *et al.* (1998) were re-analysed by Selmi & Boulinear (2001), who introduced spatial autocorrelation into the analysis to show that dispersal ability and dispersal opportunity were important in determining island biodiversity. However, human occupancy was again shown to be crucial; human visitation enhances the opportunity for groups with a low dispersal ability (e.g., mammals, insects and plants) to reach the islands. Frenot *et al.* (2005) documented the origins and current status of alien plants, micro-organisms, invertebrates and vertebrates at the islands and discussed some implications of their presence to the islands' ecosystems. Convey *et al.* (2006) drew on that information to provide an overview of the current, and likely future, significance of biological invasions on sub-Antarctic islands. These reviews focus mostly on the effects the alien organisms have on structural aspects (species richness, population sizes of particular indigenous organisms or groups of organisms, vegetation structure and composition) of the islands' ecosystems. Here, the focus is on the effects of invasive organisms on ecosystem functioning.

Ecological processes – primary production

Despite its floristic poverty, sub-Antarctic island vegetation (at least the closed plant communities at low altitudes) exhibits a high annual primary production (ANP). Total (above- plus belowground) ANPs of the island communities are higher than at the 52 Arctic and sub-Arctic sites investigated as part of the International Biological Program's Tundra Biome Project and also mostly greater than at the more temperate oceanic moorlands and bogs that were also considered to be tundra in that study (fig. 2). Even compared with temperate plant communities, ANPs of the sub-Antarctic plant communities are high. In some instances they are higher than the maximum reported for temperate North American grasslands, and they are very much in the upper part of the range reported for temperate wetlands and marshes – vegetation types that are considered to be particularly productive.

Sub-Antarctic islands have a hyper-oceanic climate with precipitation throughout the year and small seasonal and diurnal variations in temperature. This leads to a long growing season. On Marion Island, for instance, the growing season for vascular plants (at low latitudes, below about 300 m) is about 10 months (Huntley 1970) and bryophytes grow all year (Smith 1987a). Other sub-Antarctic islands have similarly long growing seasons (Wielgolaski *et al.* 1981). In contrast, Northern Hemisphere tundra communities have much shorter growing seasons, from a few weeks at high Arctic sites to about six months for sub-Arctic and alpine tundras. It is the long growing season, rather than any intrinsic capability of the plants to grow fast, that leads to the high annual primary production of sub-Antarctic vegetation. Productivity (defined here as the daily rate of aboveground production, since there are no data for belowground productivity at Northern Hemisphere tundra for comparison) is, in fact, quite low in the sub-Antarctic (e.g., between 0.9 g m^{-2} day^{-1} and 3.1 g m^{-2} day^{-1} for Marion Island vegetation; Smith 2007a). This is in part due to the cool summers experienced at sub-Antarctic islands. In contrast, sub-Arctic shrub- or dwarf shrub-dominated tundras have a growing season that, although short, is

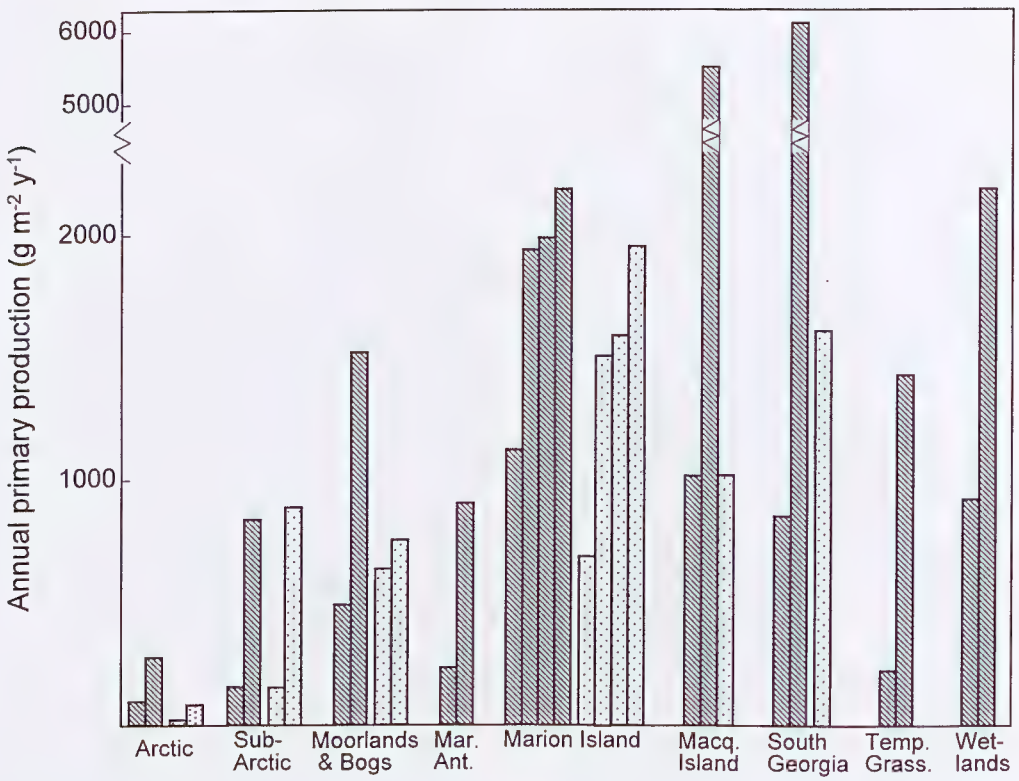

FIG. 2 – Total (above- plus belowground) annual primary production of sub-Antarctic island vegetation, Northern Hemisphere tundra, temperate oceanic moorlands and bogs, a maritime Antarctic island (Signy Island), temperate grasslands and temperate freshwater and tidal wetlands. Hatched bars are for graminoid- and/or bryophyte- dominated vegetation, stippled bars are for herb and/or dwarf shrub- dominated vegetation. For the sub-Antarctic islands each bar is for a single community. For the rest the left bar of the pair is the minimum, and the right bar the maximum, annual production reported for the particular vegetation type. Marion Island from Smith (1987a, b, 2007); Macquarie Island from Jenkin (1975); South Georgia from Clarke et al. *(1971), Lewis Smith & Walton (1975) and Lewis Smith (1984); Arctic tundra from Pakarinen & Vitt (1973), Bliss (1975), Muc (1977), Webber (1978) and Miller* et al. *(1980); Sub-Arctic tundra from Wielgolaski & Kjelvik (1973), Østby* et al. *(1975), Rosswall* et al. *(1975), and Wielgolaski* et al. *(1981); Oceanic moorlands and bogs from Doyle (1973) and Forrest & Smith (1975); Signy Island from Edwards (1973, 1974) and Collins* et al. *(1975); Temperate grasslands from Sims & Singh (1978); Freshwater and tidal wetlands from Bernard & Gorham (1978), Reader (1978), and Whigham* et al. *(1978).*

thermally more favourable for plant growth and show aboveground productivities of between 3 and 10 g m^{-2} day^{-1} (Wielgolaski *et al.* 1981). Sub-Antarctic vegetation productivity is more similar to that of sedge-moss and grass-herb communities in the higher latitude Arctic (2.2–3.3 g m^{-2} day^{-1}; Wielgolaski *et al.* 1981). These communities also have cool summers.

Another reason for the low production rates of sub-Antarctic vegetation is low irradiance. High incidence of cloud cover results in daily radiation receipt at ground level being only about 50% of that at the top of the atmosphere. This is considerably lower than at the more continental polar and sub-polar regions of the Northern Hemisphere. On Marion Island, production efficiencies (energy fixation as a percentage of energy received in the incident photosynthetically active radiation during the growing season) of the plant communities range 0.7%–2.1% (Smith 2007a), almost identical to the range (0.7%–2.4%) for sub-Arctic and Arctic tundras (Wielgolaski *et al.* 1981). This shows that, although the island vegetation grows more slowly during the growing season, it uses the incident radiation as effectively as do the Northern Hemisphere tundra vegetations. This is probably also true for other sub-Antarctic islands, although Jenkin & Ashton (1970) reported low production efficiencies (0.06%–0.46%) for Macquarie Island vegetation. However, those values were based on total radiation for the whole year, rather than photosynthetically active radiation received only in the growing season.

Ecological processes – nutrient cycling

Sub-Antarctic vegetation needs to take up substantial amounts of nutrients to support the high ANP. Marion Island plant communities require 7–27 g N, 0.5–3 g P, 5–10 g K and 2–10 g Ca per square metre per year (Smith 2007a). For some nutrients (especially N and P) the quantity taken up annually may be greater than their amounts contained in the vegetation and very much greater than the levels of plant-available forms of those nutrients in the soil. This suggests fast cycling of nutrients through the plants and rapid rates of nutrient mineralisation in the soil, contrasting with Northern Hemisphere tundra, where nutrient uptake by the vegetation is smaller, soil nutrient mineralisation rates lower, and nutrient cycling through the vegetation slower, than on the sub-Antarctic islands (Dowding *et al.* 1981, van Cleve & Alexander 1981). However, like tundra vegetation, it appears

that sub-Antarctic vegetation utilises nutrients particularly efficiently in its primary production. For Marion Island communities, the *nutrient cost of the ANP* (the total amount of N, P, K, Ca, Mg, Na, Si, Fe and Mn needed to produce 1 g of plant material, considering only the aboveground component) is between 17 and 40 mg nutrients per g ANP. Nutrient costs for the ANP have not been reported for other islands, but for South Georgia and Macquarie Island estimates are possible by combining primary production information (Jenkin & Ashton 1970, Clarke *et al.* 1971, Jenkin 1975, Lewis Smith & Walton 1975, Lewis Smith 1984) with the plant nutrient concentration information (Jenkin 1972, Walton & Lewis Smith 1980, Pratt & Lewis Smith 1982, Lawson 1985) for the two islands. This gives approximate values of 29–44 mg nutrients per g ANP, similar to those for Marion Island vegetation. For all three islands, the nutrient costs of the ANP are very much in the lower part of the range (18–135 mg g^{-1}) reported for other vegetation types, ranging from tundra to tropical forest, by Swift *et al.* (1979).

An indication of the rapid nutrient cycling on Marion Island is given in table 1, which shows the pool sizes and flux rates of nitrogen in a graminoid- and bryophyte-dominated mire. This vegetation needs to take up 25 g N per square metre per year to support the annual production. Uptake rate during peak plant growth in midsummer is 336 mg N m^{-2} day^{-1} which would deplete the plant-available N pool in about two days if that were not replenished. There is no direct nutrient input by seals or seabirds to the mire community, but most of the N in dry fallout and precipitation probably originates in rookeries and wallows on the nearby coast. However, the amount of N reaching the mire by dry fallout and precipitation, and also by biological N fixation, is negligible — only about 0.2% of the daily requirement of 336 mg N m^{-2} day^{-1}.

There is a large reserve of organic N in the mire peat and plant litter and mineralisation of the organic N is the obvious mechanism replenishing the plant-available N pool. Much effort has been devoted to estimating decomposition and nutrient mineralisation rates, using *in vitro* and *in vivo* soil incubation techniques and these yielded values which translated into very low estimates of N mineralisation rates in the field. For example, for the mire, a maximum rate of 48 mg N m^{-2} day^{-1} was found, which is only about 15% of the rate needed to meet the vegetation's daily requirement in midsummer. Smith & Steenkamp (1992a) discussed these decomposition and mineralisation studies in more detail and emphasised their limitations, the most important of which was that they concentrated on N release by microbial organisms on their own and ignored the effect of the island's abundant soil fauna. The soil fauna comprises mainly detritivores and/or microbivores which are potentially able to enhance nutrient mineralisation rates by comminuting the decomposing substrate, by chemically altering it so that it is more amenable to microbial action and by enlarging the suite of micro-organisms acting on it. Using a microcosm approach it was subsequently shown that soil macro-invertebrates (moth and weevil larvae, earthworms, snails and slugs) do, in fact, greatly stimulate rates of nutrient release from peat and litter (Smith & Steenkamp 1992b, 1993). Smith & Steenkamp (1992c) incorporated the microcosm results into a model that considered macro-invertebrate densities, peat:macro-invertebrate mass ratios, micro-organism biomasses, N pool sizes of the soil micro-organisms and of the macro-invertebrates, temporal changes in soil inorganic N concentration, and rates of N uptake by the vegetation. For the mire community considered in table 1, the model showed that macro-invertebrates cause the release of 345 mg N m^{-2} day^{-1}, sufficient to account for maximum rates of N uptake by the mire vegetation in midsummer (table 1). Hence, soil invertebrates are crucial to nutrient cycling on Marion Island and this is almost certainly true for all sub-Antarctic islands.

Threats to ecological processes caused by invasive alien organisms

If the rate of nutrient release from decomposing organic matter limits primary production at sub-Antarctic islands, and soil invertebrates are crucial facilitators of decomposition, any factor impacting on the soil invertebrate populations is likely to affect nutrient cycling and vegetation production at the islands. House mice (*Mus musculus* Linnaeus, 1758) have been introduced to most sub-Antarctic islands. On Marion Island their population (at least in summer and autumn) has recently increased, possibly in response to an ameliorating climate (Van Aarde & Jackson 2007) and/or the eradication of the island's feral domestic cats in the early 1990s (Ferreira *et al.* 2006). The mice feed mainly on soil macro-invertebrates (Crafford 1990a, Smith *et al.* 2002) and they can annually remove up to six times the instantaneous biomass of a particular macro-invertebrate prey species. Since most of the prey species have long life-cycles the mice must impact severely on their populations, and the densities of

TABLE 1
Pools and fluxes of nitrogen in a mire community at Marion Island*

Pool / flux	Size / rate
Annual amount taken up by vegetation	25 000 mg N m^{-2} y^{-1}
Uptake rate in midsummer	336 mg N m^{-2} day^{-1}
Plant–available N pool	700 mg N m^{-2}
Precipitation and dry fallout input	0.6 mg N m^{-2} day^{-1}
Biological N fixation	0.2 mg N m^{-2} day^{-1}
Organic N pool	388 000 mg N m^{-2}
N mineralization by microorganisms alone	48 mg N m^{-2} day^{-1}
Soil macroinvertebrate–stimulated N mineralisation	345 mg N m^{-2} day^{-1}

* from Smith (1988) and Smith & Steenkamp (1992c)

the preferred prey (moth larvae, weevil larvae and adults, and spiders) have declined significantly at the island (Hänel 1999).

Predation by mice on terrestrial macro-invertebrates can be expected to result in decreased rates of nutrient mineralisation, which will decrease not only the quantity but also the quality (nutrient status) of plant material in the primary production. This will result in lower quality litter (Smith 2007a) that will decompose even more slowly. Changes in the balance between peat accumulation and decay will have implications for ecosystem structure since that balance determines the hydrological regime, which directs vegetation succession on the island (Gremmen & Smith 2007).

Another consideration in the interaction between house mice, soil macro-invertebrate and nutrient cycling is that the European slug, *Deroceras panormitanum* (Lessona & Pollonera, 1882), introduced to the island in the mid- to late 1960s (Smith 1992) is now widely distributed and abundant in some habitats. Slugs are rarely preyed on by mice (Smith *et al.* 2002) but, like the indigenous macro-invertebrates, they markedly stimulate rates of nutrient mineralisation (Smith & Steenkamp 1992b). Thus, slugs can potentially replace indigenous macro-invertebrates as nutrient recyclers in areas of high mouse density. However, Smith (2007b) showed that there are qualitative and quantitative differences in decomposition/ mineralisation mediated by slugs and the indigenous soil macrofauna. For instance, the ratio of C to N mineralised by slugs from plant litter is 372:1 whereas for mineralisation by moth larvae (the most important mediators of nutrient release in most habitats on the island) it is 541:1 (difference significant at P=0.011). In contrast, the C:P ratio released by slugs (4735:1) is not significantly different to that released by moth larvae (4380:1). These differences will lead to altered nutrient quality of the decomposing substrate, and ultimately to a shift in the balance between primary production and decomposition. The substitution, or partial substitution, of indigenous macro-invertebrates by slugs as facilitators of decomposition and nutrient cycling will be thus affect ecosystem structure and functioning on Marion Island.

Other introduced detritivores at the island are the chironomid midge *Limnophyes minimus* (Meigen, 1818) and a porcellionid isopod *Porcellio scaber* (Latreille, 1804). In some habitats midge larvae ingest greater amounts of litter than do the indigenous moth larvae (Hänel & Chown 1998) and the large bodied isopod is also likely to ingest large quantities of litter (Slabber & Chown 2002). Both will influence nutrient cycling, but studies like the one on the slugs are needed to establish their exact qualitative and quantitative effects. If an introduced species possesses a different habit to the one it might compete with or even replace, the influence on ecological processes might be substantial, even if the two are taxonomically similar. For instance, all sub-Antarctic islands have indigenous earthworms. Their habit, like all the introduced earthworms reported until recently, is *epigeic* (live in the organic surface layer of soil, and in the overlying litter layer, feed on organic debris only). In 2004 a new earthworm species, *Allolobophora chlorotica* (Savigny, 1826), was found at Îles Kerguelen, only near the glasshouses at Port-aux-Francais, suggesting that it was a recent introduction (Convey *et al.* 2006). The habit of *A. chlorotica* is a mix of *endogeic* (live in complex lateral burrows that extend through all layers of upper mineral soil, and eat mineral soil as well as organic matter) and *anecic* (build vertical burrows that extend from the soil surface well into the mineral soil, feed on surface litter and cause vertical mixing of material in the soil profile). Convey *et al.* (2006) suggest that the habits of this species, especially the burying of organic matter in mineral soil, will have significant consequences for pedogenesis at the island, and it is quite likely that this will affect rates of nutrient cycling.

Changes in nutrient inputs by seabirds

Seabirds feed in the ocean and deposit substantial amounts of nutrients in the form of guano and moulted feathers on sub-Antarctic islands. A large proportion of the nutrients are added on the coast, at large penguin rookeries, and much of that washes back to the ocean without being incorporated into the soils or vegetation. However, there is substantial volatilisation of nitrogen as ammonia off the rookeries, some of which is deposited inland (Lindeboom 1984). In addition, birds that breed inland (mainly albatrosses, skuas, petrels and prions) have a significant effect on the productivity and nutrient status of the vegetation (Smith 1976a, 1978), and also on other aspects related to ecological functioning, such as the size and activity of soil micro-organism populations (Smith & Steyn 1982, French & Smith 1986, Grobler *et al.* 1987), rates of cellulose decomposition (Smith *et al.* 1993) and soil respiration (Smith 2003).

The populations of the surface-nesting species at Marion Island have declined since the mid-1970s (Crawford *et al.* 2003). Amongst the reasons suggested for this (Ryan & Bester 2007) is a decreased food availability caused by overfishing in the Southern Ocean (and possibly increased competition for food by a rapidly increasing fur seal population), mortality associated with long-line fishing and, for the Southern Giant Petrel, possibly disturbance at breeding colonies. The decline in the seabird populations has resulted in a smaller nutrient input of avian products to the island. Between the 1974/75 and 2002 the inputs of N, P and Ca through guano and moulted feathers of surface-nesting birds declined by 4–11% in the shore zone and by 37–47% inland (fig. 3).

The data in figure 3 reflect the influence of only the surface nesters. In 2002 it is estimated that burrowing petrels and prions added about 185 tonnes N, 18 tonnes P and 48 tonnes Ca to the Marion Island's ecosystem, much of that inland (Smith & Froneman 2007). It is not known what the amounts added by burrowers was in the 1970s since there are no population estimates for that period. However, it is known that domestic cats, which were introduced in 1949 and quickly became feral, had a deleterious effect on the populations of most, if not all, of the burrowing species. By 1975 the cat population was about 2000 and it was estimated that they killed about 450 000 burrowing birds per year (Bester & Skinner 1991). Tussock grassland comprising nitrophilous plant species is the climax vegetation of slopes occupied by burrowing birds and is supported by the nutrients by them (Smith 1976a). In 1971/72 tussock grassland occupied about 1% of the lowlands on the northeastern part of Marion Island (Smith 1976b, 1977). By 1991 this had decreased to 0.1%, and by 2005 tussock grassland had completely disappeared from the area, being replaced mostly by low-nutrient status communities such as fernbrake. The decline is ascribed to the disappearance of burrowing bird colonies caused by cat predation (Gremmen & Smith 2007), even though the cats were eradicated in

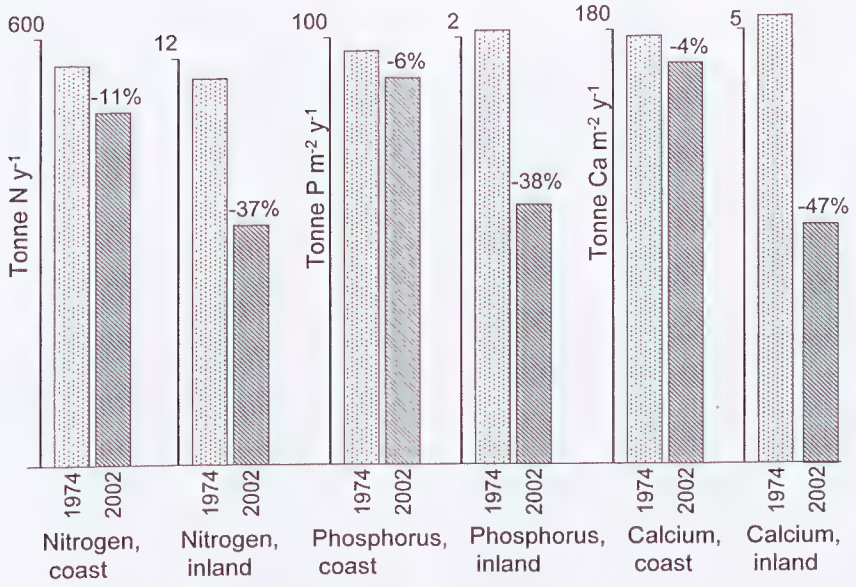

FIG. 3 – The amounts of nitrogen, phosphorus and calcium added annually as guano and moulted feathers of surface-nesting seabirds to the coastal and inland areas of Marion Island in 1974/75 and 2002/03. From Smith & Froneman (2007).

1991 (Bester *et al.* 2000). The petrel and prion populations do appear to be recovering (Cooper *et al.* 1995) but this has not yet led to the establishment of significant inland colonies. Tussock grasslands are widespread on nearby Prince Edward Island, where burrowing bird densities are also much higher and where cats were never present.

Climate change and its effects on ecosystem function

The sub-Antarctic climate has changed significantly over the past 40 years. Substantial warming has occurred at Macquarie Island (Adamson *et al.* 1988), South Georgia (Gordon & Timmis 1992), Marion Island (Smith 2002), Îles Kerguelen (Frenot *et al.* 1997) and Heard Island (Budd 2000). In the same period total annual precipitation has decreased on Marion Island and Îles Kerguelen but has increased on Macquarie Island. Smith & Steenkamp (1990) proposed some scenarios of the direct effects of warming (and drying) for the biota of Marion Island, but there have been few studies specifically focusing on the effects of climatic change on ecosystem processes in the sub-Antarctic. Most have concentrated on the ecophysiological responses of particular organisms (or groups of organisms) to abiotic factors such as moisture, light and temperature and it is only possible to speculate on the functional implications of climate change from their results.

Since primary production and decomposition rates are limited by low temperature and, in some plant communities, by soil moisture contents that are either sub-optimal or supraoptimal for soil microbial activity, climate change will directly influence ecological functioning at the islands. It is uncertain what effects warming will have on primary production. Photosynthetic optima of the sub-Antarctic and maritime Antarctic plants studied to date are above mean air temperatures at the islands on which they occur (Collins 1977, Bate & Smith 1983, Pammenter *et al.* 1986, Edwards & Lewis Smith 1988, Smith & Gremmen 2001), so warming is expected to increase carbon assimilation rate. All sub-Antarctic plants have the C_3 photosynthesis pathway and might be expected to show increased rates of CO_2 assimilation in response to the increasing atmospheric CO_2 concentration being experienced in the sub-Antarctic (Smith 1991, Yoshikawa-Inoue & Ishii 2005). Hence, sub-Antarctic vegetation should become more productive under the current regime of warming and CO_2 enrichment. However, so far the only studies of the influence of climatic change on primary production have been limited to individual species and do not give an unequivocal picture. For example, Smith & Gremmen (2001) showed that changes in temperature and radiation at Marion Island by the amounts known to have occurred there in the past 35 years (temperature increased by 2°C, total irradiation by 10%) have a negligible effect on the annual amount of carbon acquired by the lichen *Turgidosculum complicatulum* ((Nyl.) J. Kholm. & E. Kholm.) (= *Mastodia tesselata,* Hook. f.& Harv., 1845), provided the thalli remain hydrated. Even more drastic changes – temperature up by 4°C and radiation up by 20% – will have a negligible effect on annual carbon acquisition by the lichen, again provided the thalli stay hydrated. Incorporating hydration/desiccation cycles into the model resulted in a lowering of annual net C uptake compared with current levels, but the reduction varied greatly depending on whether atmospheric drying or thallus drying was considered. However, these findings might not be pertinent for carbon acquisition by the vegetation, in which vascular and bryphyte species are much more important than lichens.

Soil respiration rate on Marion Island increases with increasing temperature and with soil moisture content up to field water-holding capacity (Smith 2003, 2005). It is likely that waterlogging depresses respiration rate. This has not been tested, but soil decomposition potential (measured as the loss in tensile strength of buried cotton strips) is lower at waterlogged (and at very dry) sites than at mesic sites (Smith *et al.* 1993); the same has been shown for other sub-Antarctic islands (Walton 1985, Lawson 1988) and also on maritime Antarctic Signy Island (Davis 1986, Wynn-Williams 1988). The rate of decomposition mediated by microbes alone should thus increase with warming, and will

either increase or decrease with wetting/drying depending on the current soil moisture regime at the particular plant community. Warming also increases the rate at which the island's insects and earthworms process plant litter and peat (Crafford 1990b, Smith & Steenkamp 1990), leading to greater rates of nutrient release. However, ecophysiological studies on the island's weevil species (important agents of nutrient mineralisation in many of the habitats) show that upper lethal temperature for a particular species corresponds closely to the maximum microclimate temperature in the habitats occupied by that species (Van der Merwe *et al.* 1997), suggesting that climatic warming might be deleterious to the weevils' survival. Similarly, flightless moth larvae are probably the most important facilitators of nutrient release on the island and Klok & Chown (1997) showed that continued warming will have a profound negative effect on the moth population, especially if the warming is accompanied by increasing aridity. Hence, climate warming could affect the island's insect populations directly, as well as indirectly by allowing a larger population of house mice at the island. Both effects are detrimental to the insect populations and will lead to decreased rates of nutrient recycling and lower primary production.

Other scenarios of the effects of climate change on ecosystem function can be proposed. For instance, if changing oceanic and atmospheric circulation patterns underlie the climate change being experienced at sub-Antarctic islands, as suggested by Adamson *et al.* (1988) and Rouault *et al.* (2005), then this could affect the the trophic dynamics of the seal and seabird populations by moving their feeding grounds, or making it harder/easier for them to reach the feeding grounds. This might be one reason for the decline in seabird populations at Marion Island. As mentioned above, the input of nutrients in avian products is an important determinant of all aspects of ecosystem functioning at Marion Island, and this is true for all sub-Antarctic islands.

Probably the most important effect of a warming climate is that it increases the ease with which invasive alien organisms can become established on sub-Antarctic islands (Bergstrom & Chown 1999). Coupled with increasing human visitation and occupancy of the islands, the major source of introduced organisms (Chown *et al.* 1998, 2005, Whinam *et al.* 2005), it is likely that the rate of establishment of invasive biota on sub-Antarctic islands will increase. This is already happening. On Marion Island the number of new introductions has increased in the past decade, despite stringent measures having been put into place to prevent this (Slabber & Chown 2002). At South Georgia there has been an explosion of several long-established, but previously alien plant populations due to the production of viable seed (which was not achieved until a few decades ago), several species that were recorded as rare transient aliens have suddenly reappeared at their former sites (presumably from a buried seed bank), and new species have also recently appeared (information on South Georgia kindly provided by Ron Lewis Smith). The pace of recent human-mediated introductions of spiders to islands in the Southern Ocean is at least 30 times more rapid than introductions resulting from natural dispersal (Pugh 2004). Like the examples of the introduced house mice and slugs at Marion Island, new introductions that succeed in becoming invasive are likely to have insidious, but profound, effects on ecosystem functioning on the sub-Antarctic islands.

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RESEARCH ACTIVITIES IN THE SUB-ANTARCTIC

by Yves Frenot

(with two text-figures and one table)

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Current scientific activity in the sub-Antarctic islands is assessed in the context of past achievements and potential future issues. Brief mention is made of the scientific expeditions of the nineteenth and twentieth centuries. A survey of international bibliographic databases revealed the dominance of research in the life sciences, reflecting the unique characteristics of sub-Antarctic ecosystems. Research and monitoring in geosciences are also important components of scientific activities in these islands. Climate change and non-native species are two issues which dominate current and probably future studies in the sub-Antarctic.

Key Words: sub-Antarctic, research, science, bibliography, scientific expeditions.

INTRODUCTION

Although the surface area of the sub-Antarctic islands may appear negligible, they are fascinating locations for research. Much of the interest scientists show in these remote spots centres on their ecological characteristics.

First, they are geographically isolated: each island is several thousand kilometres from the nearest continent. Their relatively late discovery, at the end of the eighteenth century or later, kept the region free of human influence (and of research activities) until very recently.

While their climatic conditions vary slightly with their positions relative to the Polar Front, these islands are characterised by a hyperoceanic climate, with, for example, cool temperatures close to 0°C throughout the year, high precipitation and strong winds (see Convey 2006). The climate is not as extreme as in Antarctica, but it constitutes a major constraint for the development of many organisms which in the sub-Antarctic are at the limit of their distribution.

As a consequence of the islands' isolation and climatic conditions, biodiversity, which is relatively high in marine ecosystems, is very low in terrestrial habitats. This is illustrated, for example, by the low number of native plant species. The rate of endemism, however, is relatively high and morphological adaptations such as apterism of insects are common. The sub-Antarctic ecosystems are also characterised by a significant level of nutrient transfer between the terrestrial and marine environments via seabirds and seals.

Indigenous species such as herbivorous and carnivorous land mammals that play a major role in continental ecosystems are absent from the natural sub-Antarctic terrestrial ecosystems. Combined with the very high primary production of many plant communities, this lack has a significant effect on ecosystem structure and function. Predators are rare (there are some predatory spiders and insects) and energy flow is controlled by detritivores such as fungi and bacteria or saprophagous invertebrates, rather than by herbivores.

These characteristics explain why the sub-Antarctic terrestrial ecosystems are relatively simple compared with those in more temperate regions, and why they can be sensitive to environmental changes. Because they also provide breeding habitats for a huge number of marine birds and mammals, the sub-Antarctic islands constitute ideal sites for ecological research.

The aim of this paper is to present a brief overview of scientific research in the sub-Antarctic in the context of past achievements and potential future issues. The objective is not to provide a detailed assessment of the activities carried out in each island, but rather to stress some common features, mainly through the analysis of the sum of publications produced about this region.

This overview concentrates mainly on the narrow belt between the Subtropical Convergence and the Polar Front. Only islands close to the oceanic Polar Frontal Zone, where cold Antarctic waters sink below a warmer surface layer, are considered, namely South Georgia, Marion and Prince Edward, Crozet, Kerguelen, Heard, McDonald, and Macquarie islands.

THE PRE-1950 PERIOD

The sub-Antarctic islands were discovered relatively late, most of them at the end of the eighteenth century, by sailors such as Cook and Kerguelen who searched for *Terra Australis Incognita*. Macquarie Island was discovered later, in 1810, and Heard Island only in 1853, after the discovery of the Antarctic continent. Very soon after their discovery, human visits focused almost exclusively on economic exploitation of wildlife: fur seal skins, elephant seal oil and penguin oil.

Although the *Challenger* Expedition (1872–76) was designed to explore the depths of the sea, it provided the first opportunity for scientists to visit a number of sub-Antarctic islands: Prince Edward, Kerguelen and Heard islands. The shoreline of the McDonald islands was surveyed on that occasion and geological and botanical samples were collected on Heard Island. In 1874, Îles Kerguelen were also a base for the observation of the Transit of Venus by the *Gazelle* Expedition.

The first scientific expedition to South Georgia was the German International Polar Year Expedition of 1882–83. Eleven men spent a year at Moltke Harbour in Royal Bay to implement a varied scientific program and to observe the Transit of Venus. A biological survey was carried out by the Swedish South Polar Expedition in 1902.

During the German *Gauss* Expedition (1901–03) valuable investigations were conducted in geology, geography, earth-magnetism, oceanography, meteorology and biology. A base station was established at Observatory Bay on Îles Kerguelen in 1901 and the expedition also visited the Îles Crozet.

The German *Deutschland* Expedition visited South Georgia three times in 1911 and 1912 and made the first real survey of the interior of the island. Over the same period, the Australasian Antarctic Expedition (AAE, 1911–14) established the first meteorological station at Macquarie Island, and carried out the first significant biological and geological surveys there.

After the end of the Second World War, several stations were established, some of them permanently, others temporarily (table 1).

TABLE 1
The sub-Antarctic permanent stations

Island (nationality of station)	Year of permanent station establishment	Average number of people in winter
Marion (South Africa)	1948	25
Macquarie (Australia)	1948	20
Heard (Australia)	1947 (closed in 1955)	
South Georgia (UK)	1950	5
Kerguelen (France)	1951	60
Crozet (France)	1962	25

THE PERIOD 1950–75

Permanent stations were established on most of the sub-Antarctic islands during this period. After the end of the Second World War, the objectives of the governments were obviously to affirm their sovereignty on these islands.

Control of Heard Island, for example, was disputed by the United States and the sovereignty of Heard and McDonald islands was transferred from Britain to Australia as soon as the Atlas Cove station opened (Green 2006). In 1960, Madagascar became independent and claimed the French sub-Antarctic islands located in the Southern Indian Ocean (Crozet, Kerguelen). While Port-aux-Français Station had, by then, already been continuously occupied for nine years on Kerguelen, the necessity to affirm French sovereignty on Îles Crozet was probably one of the main reasons for the establishment of the Alfred Faure station at Possession Island, Crozet archipelago.

The second purpose of the establishment of permanent stations in this region was to set up meteorological observatories. Despite the development of aviation, travelling by sea remained the main means of cargo and passenger transport between the continents. The establishment of meteorological stations contributed to increased safety in the "Roaring Forties". South Africa, for example, set about annexing Marion and Prince Edward islands in December 1947 and a meteorological station was set up in 1948 (Prince Edward Islands Environmental Management Plan 2005).

Generally, few coordinated research programs were undertaken in the first years of occupation. The major exception was the first scheduled research visit to both Marion and Prince Edward islands in 1965: the South African Biological and Geological Expedition was initiated and led by Edward M. van Zinderen Bakker Sr. The extensive results published in 1971 marked the start of a new era in research activities in the sub-Antarctic.

FROM THE MID-1970S TO THE PRESENT

In order to assess the diversity of recent scientific activities in the sub-Antarctic islands, I have analysed publications stored in several databases available through the web. These are: *Science & Technology Current Contents Search®* produced by Thomson Scientific – Institute for Scientific Information; *Inspec®* produced by the Institute of Electrical Engineers; *Medline* produced by U.S. National Library of Medicine; *International Science Database* produced by INIST-CNRS; and *Pascal* produced by INIST-CNRS.

The search for relevant publications was carried out using the Webspir multibase search tool produced by INIST-CNRS (http://biblioscience.inist.fr/ access submitted to subscription). The search was restricted to the period 1975–2006. The character string "sub-antarc*" or "subantarc*" in title, key words or abstract was searched. Another search was performed using the name of one of the islands or island groups considered here (South Georgia, Marion, Prince Edward, Crozet, Kerguelen, Heard, McDonald, and Macquarie islands). Results were checked to eliminate duplicated or inappropriate references (for example, publications related to Marion Island in the Arctic). Each reference was placed into one of seven arbitrary scientific fields, namely: terrestrial ecology; marine ecology; geosciences; human biology and medicine; human impact research; environmental management; and taxonomy, systematics and biogeography.

The search retrieved about 3310 scientific references dealing with the sub-Antarctic region as defined here. Some deal exclusively with marine science and reported on oceanographic expeditions which took place in the sub-Antarctic region. These data have been discarded and a total of 2716 references, restricted to the sub-Antarctic islands themselves or their coastal and near-shore marine environment, were examined.

This total underestimates the high productivity of the scientists working in this area: most of the studies carried out at the beginning of the period under consideration were published in reports, journals or books not indexed in the analysed databases. For example, the numerous papers included in the report of the Marion and Prince Edward Islands Expedition (1965) are not present in the list. Similarly, the important works published in the *British Antarctic Survey Bulletin* are absent. However, it may be assumed that this bias is the same for all islands and this list of references is likely to be a reflection of the importance of each field of activity.

The distribution pattern of scientific fields is shown in figure 1. Most studies carried out in the sub-Antarctic are related to terrestrial ecology. More than 100 publications per year have been produced in this domain during the last 10 years. By comparison, marine ecology is less studied but remains one of the main scientific issues. As a result, 67% of the studies deal with ecosystem functioning, population dynamics, adaptation, ecophysiology or genetics.

Among the 1157 references related to terrestrial ecology, most concern marine vertebrates, birds and seals, followed

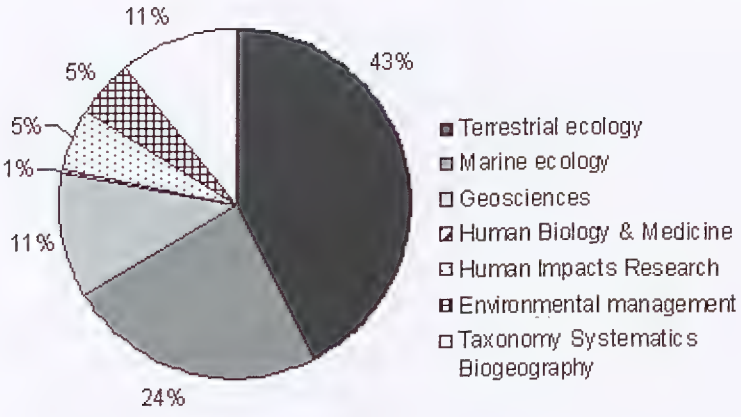

FIG. 1— Distribution of the sub-Antarctic articles published between 1975 and 2006 in different scientific fields.

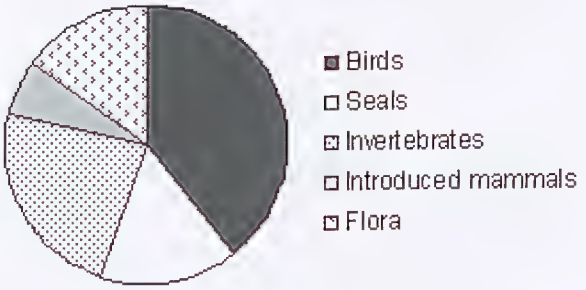

FIG. 2 — Distribution of the publications in terrestrial ecology according to their main topic.

by invertebrate fauna and flora (fig. 2). In addition, a significant number of studies have been carried out on the introduced mammals.

Two "new" scientific fields are emerging: publications on climate change appeared for the first time at the end of the 1980s, and account for 10% of the publications in 2003–06. Similarly, the number of papers related to alien species and their impact on the native communities or ecosystems markedly increased in the 1990s and accounts now for about 10% of the publications. These changes probably result from the influence of two successive SCAR programs, BIOTAS (Biological Investigations of Terrestrial Antarctic Systems) and RiSCC (Regional Sensitivity to Climate Change in Antarctic Terrestrial Ecosystems), which initiated and coordinated most of the research in the sub-Antarctic terrestrial ecology.

Research in taxonomy and biogeography is also an important component of the scientific activity (fig. 1). A total of 221 references (11% of the total publications) was identified in taxonomy and systematics, 144 concerning terrestrial biota and 77 concerning marine biota. A total of 105 publications relates to the biogeography and history of colonisation of sub-Antarctic islands.

Geosciences account for about 11% of the research activity, mainly in the field of geology and, to a lesser extent, glaciology, seismology, geomagnetism, ionosphere and atmosphere chemistry. It is interesting that no publications are directly linked to meteorological observations, although climatic data are available through international databases or publications on climate change.

More than 5% of the publications concern environmental management: conservation issues (2.7%), control or eradication of species (1.2 %) and management policy (1.6%). Among this last category are several articles on cultural heritage and conservation of historic remains.

Finally, 1% of the publications relate to human biology and medicine. They mainly concern human behaviour such as the coping strategies used by expeditioners during overwintering.

The bibliographic survey emphasises the dominance of research in the life sciences. The oldest but still important area concerns taxonomy and biogeography. The high rate of endemism is a very interesting issue to biologists who sometimes call these islands the "sub-Antarctic Galapagos". Sub-Antarctic data also have been used extensively in the discussions on insularity theory (see e.g., Vitousek *et al.* 1995). Today, the development of molecular biology offers another avenue of taxonomic investigation.

Another characteristic of research in the sub-Antarctic is the regular support by national agencies of long-term studies, support which is probably stronger than elsewhere in the world. For example, data on bird populations in the French sub-Antarctic islands have been collected for more than 40 years (Weimerskirch *et al.* 2003). These long-term data are extremely useful in understanding the impact of environmental changes on these animals. For example, the decline in numbers of Wandering Albatrosses was probably related to the impact of fisheries around Kerguelen, Marion and Crozet islands (Weimerskirch *et al.* 1997). These results led to changes in fishing techniques and the populations are now recovering. These data can also reveal the susceptibility of species to climate change or the impoverishment of food resources.

The impact of climate change on terrestrial and marine sub-Antarctic ecosystems has become a significant issue. Temperature increases, amongst the most rapid in the world, are well documented in the sub-Antarctic, with reports from several locations of increases in annual air temperatures of at least 1°C over the last 30–50 years. Decreasing precipitation has been reported at Marion and Kerguelen islands since the early 1970s. Most of the sub-Antarctic glaciers at Heard Island, Îles Kerguelen and South Georgia are currently retreating. The changes have strong impacts on terrestrial ecosystems, such as decline in water availability and desiccation of the native vegetation in some locations (Convey 2006).

Simultaneously, introduction of alien species is probably the second most important threat to sub-Antarctic ecosystems and many studies on this issue have been initiated in recent years (e.g., Frenot *et al.* 2005). The current warming may have important biological consequences. It could be

responsible for the success or failure of the establishment of new species, particularly ectothermic organisms unable to regulate their own temperature and living at temperatures close to their threshold for development.

Several eradication or control programs have been attempted, some of them successfully. For example at Marion Island, cats, which were responsible for the near local extinction of some bird species, were successively trapped, subjected to a viral disease, poisoned and shot during the 1980s. The last time a cat was seen on the island was in 1991 (Bloomer & Bester 1992). It is now believed that complete eradication of feral cats on Marion Island has been achieved and burrowing petrels, which were severely affected by the cats, have now shown signs of recovery.

Although there is no doubt that the life sciences are the major component of scientific activities in the sub-Antarctic, the present bibliographic survey probably underestimates activity in the geosciences. Several geological studies and maps are now available. These islands are geologically interesting as most of them are true oceanic islands, with no relation to former continents (e.g., Quilty 2006). They are generally associated with marine ridges or zones of contact between large plates and they provide useful information on the nature of deep materials from the Earth's mantle.

Finally, one of the most underestimated areas is probably the research associated with observatory and monitoring activities. The sub-Antarctic islands fill a gap in a vast expanse of ocean by providing sites where extremely rare and valuable data of global interest can be monitored. In this context, meteorology was usually one of the first scientific activities implemented in the sub-Antarctic islands and the stations are crucial for understanding the global climate. Similarly, the participation of the sub-Antarctic observatories in different fields of earth science such as seismology, geomagnetism, and atmospheric chemistry as part of global networks is crucial to increasing the quality of modelling and our understanding of processes at a global level.

CONCLUSION

One of the main conclusions of this study is that there is no "sub-Antarctic scientific research" but research carried out in the sub-Antarctic. However, the scientific activity in this region is clearly related to the particular characteristics of the islands and their ecosystems.

Scientific collaborations between researchers on various sub-Antarctic islands has increased significantly during the past decade. For example, the former RiSCC program, supported by SCAR, allowed the development of collective studies to analyse the impact of climate change on the biodiversity and ecosystems of the Antarctic and sub-Antarctic regions. In 2004, expeditions were conducted on Heard, Kerguelen and Marion islands to make simultaneous observations and measurements on common plant and invertebrate species, using exactly the same protocols.

In the near future, the main scientific issues in the sub-Antarctic clearly will be related to climate change, non-native species, and human impacts on biodiversity and ecosystem functioning. From these points of view, the sub-Antarctic islands will provide important pointers to changes that could occur in more southerly areas, namely in the Antarctic Peninsula. They give key opportunities to improve our understanding of the consequences of climate changes on terrestrial habitats and, more generally, to improve our knowledge of ecosystem functioning.

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RENEWED MANAGEMENT SYSTEM AND PROVISIONS FOR SOUTH AFRICA'S SUB-ANTARCTIC ISLANDS

by Sarah J. Davies, Steven L. Chown and Leonie S. Joubert

(with three tables)

Davies, S.J., Chown, S.L. & Joubert, L.S. 2007(23:xi): Renewed management system and provisions for South Africa's sub-Antarctic islands. *Papers and Proceedings of the Royal Society of Tasmania* 141(1): 115–120. ISSN 0080-4703. DST-NRF Centre of Excellence for Invasion Biology, Department of Botany and Zoology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa. (SJD*, SLC, LSJ). *Author for correspondence.

A novel environmental management plan (EMP) produced for the Prince Edward Islands provides a systematic and comprehensive set of provisions for the management of the islands' biodiversity and historical estate. The plan addresses four major management goals: administration, conservation management, historical conservation and waste management. The EMP serves both an information-provision and a management-support function within a framework of continual improvement.

Key Words: biological invasions, quarantine, waste management, environmental management plan, Prince Edward Island, Marion Island.

INTRODUCTION

The Prince Edward Islands are situated in the Indian Ocean sector of the Southern Ocean approximately 1770 km southeast of the South African mainland. The group consists of two islands separated by 19 km: the larger Marion Island (46°54'S, 37°45'E, 290 km²) and the smaller Prince Edward Island (46°38'S, 37°57'E, 45 km²). Marion Island has a well-established research base that has been staffed by a team of technicians and scientists since the annexation of the island by South Africa in 1948. Generally, a single re-supply voyage occurs annually, but in recent years, with the construction of a new research base, visits to supply construction materials and personnel have become more frequent (up to four voyages annually). Prince Edward Island is visited infrequently, having the highest protection status afforded to any land in the territory of South Africa. It also has no infrastructure. The relatively untransformed state and comparatively simple ecosystems of the islands have made them ideal sites for an active and productive bio-physical research programme (e.g., Hänel & Chown 1999).

The Prince Edward Islands enjoy greater protection than any other land area in South Africa by virtue of their unusual and sensitive biodiversity, which is unique to the few land masses in the Southern Ocean, and in some cases specific to one or both of the islands in the group (Chown *et al.* 2001). Although the islands are designated a Special Nature Reserve, conservation threats are substantial. Alien species have already been implicated in local species extinctions and have resulted in altered ecosystem functioning (Chown & Smith 1993, Gremmen *et al.* 1998, Bergstrom & Chown 1999, Bester *et al.* 2002), with further impacts expected as environments continue to change and as new species establish (e.g., Lee *et al.* 2007).

The effects of climate change and illegal, unregulated and unreported (IUU) fishing are already evident at the islands (Chown & Smith 1993, Nel & Nel 1999, Lombard *et al.* 2007). Further introductions of alien species in the form of pathogens have the potential to cause disease outbreaks which could severely affect species and ecosystems of conservation concern (Daszak *et al.* 2000).

The first management plan for the Prince Edward Islands was published in 1996, in response to the 1995 proclamation of the islands as a Special Nature Reserve in South African law (Department of Environmental Affairs and Tourism [DEAT] 1996). Although regular review and modification of the management plan was envisaged at the time, the first update was commissioned in 2005 and the drafting of the updated Prince Edward Islands Environmental Management Plan (EMP) was completed early in 2006. During the intervening nine years, the national and international political and legal contexts changed fundamentally, and South Africa now has an advanced set of environmental laws based on an environmental umbrella act (National Environmental Management Act, No. 107 of 1998; Office of the President 1998) that provides for cooperative governance and establishes principles for decision-making. In short, environmental management in South Africa now places people and their needs at the forefront of its concern, and aims to drive development that is socially, environmentally and economically sustainable. Through the National Environmental Management Act, government has established the legislative framework for several sectoral daughter acts such as the National Environmental Management: Protected Areas Act (No. 57 of 2003; The Presidency 2004a) and the National Environmental Management: Biodiversity Act (No. 10 of 2004; The Presidency 2004b), and a number of new institutional structures (e.g., an intra-governmental environmental coordinating committee). In concert with these changes in the regulatory environment, advances in scientific knowledge and environmental practice during the intervening period have altered the range of tools and the quality of information that is available to environmental managers.

APPROACH AND METHODS

The new Environmental Management Plan (EMP) was developed by the Department of Science and Technology-National Research Foundation (DST-NRF) Centre of Excellence for Invasion Biology under contract to DEAT. The

drafting process took place over a 10-month period during 2005 and included a review of the previous management plan, intensive examination of legislation and policy and other island management plans, and consultation with academic, public- and private-sector participants in sub-Antarctic operations. Three attributes set this plan apart from the previous Prince Edward Islands Management Plan and from many other management plans.

First, the updated EMP is based on the International Standards Organisation (ISO) principles of quality management, emphasising a systems approach to management, a factual approach to decision-making, and the need for continual improvement. Although the EMP was produced as a specific requirement of national legislation, the ISO 14000-series approach brings the plan in line with international standards normally used in voluntary adherence systems.

Second, an integrated life-cycle approach has been used to take into account all phases of project development, from planning and policy-making to implementation and review.

Third, the management provisions of the plan are comprehensive and clearly articulate the actions, targets and roles, and monitoring and remedial actions that will guide management responses to routine and extraordinary situations (table 1). The EMP also serves to provide information for all visitors to the islands since it contains a comprehensive background to the physical, biological and social environment of the islands.

OBJECTIVES OF THE PLAN

The objectives of the EMP are to conserve and, where necessary, restore biophysical systems on the islands; to meet South Africa's international commitments to Southern Ocean conservation (through at least 20 relevant agreements and protocols, principally the Convention on Biological Diversity, Convention on the Conservation of Antarctic Marine Living Resources, Convention for the Conservation of Antarctic Seals, Agreement on the Conservation of

TABLE 1
A single management objective and its provisions, Prince Edward Islands[1]

Objective	Actions	Target	Monitoring actions	Responsibilities	Remedial actions
Minimisation and safe handling and storage of waste generated at the field huts	No uncooked meat, fish, chicken or egg products may be supplied to or transferred to or stored at the field huts	Minimise generation of bio-hazardous (high risk) waste	Inspections of food during hut re-supply; self-regulation by all over-wintering and take-over personnel	Action: all visitors, DEAT DAI Monitoring: SCO and TCO	Any bio-hazardous waste found at the huts must be containerised and returned to the base for freezing; origin of waste must be ascertained and followed up with suitable penalties
	Carry out all bones, paper, cardboard, batteries etc. and enter into base waste stream	Minimisation of waste accumulation at the field huts	*Ad hoc* observation of activities at the field huts and one-to-one communication with team members	Action: team members and take-over visitors Monitoring: TCO/SCO	TCO/SCO to inform DEAT DAI of breaches and DEAT to revoke permits if necessary
	Rinse cans and bottles and place in the waste bins at the huts	Safe storage and handling of waste	*Ad hoc* observation of activities at the field huts and one-to-one communication with team members	Action: team members and take-over visitors Monitoring: TCO/SCO	TCO/SCO to inform DEAT DAI of breaches and DEAT to revoke permits if necessary
	Decommission and close or, where possible, remove contents of all pit toilets and replace with removable bucket system	Minimisation of persistent pollution; safe storage and handling of waste	Annual reporting of DEAT DAI, submitted to PEIMA	Action: COs, DEAT DAI Monitoring: PEIMA	Annual reporting of PEIMA to DEAT DG should point out lack of action on this point
	Replace all field hut toilet containers at least once per year, whether full or not	Safe storage and handling of waste	Ensure that take-over schedule accommodates resupply and waste removal at all field huts	Action: COs Monitoring: Team leader	None

[1] This example is taken from Goal 7-1-1: Appropriate and sustainable management of waste at the Prince Edward Islands. CO = Conservation Officer; DEAT = Department of Environmental Affairs and Tourism; DAI = Directorate Antarctica and Islands; DG = Director General; SCO = Senior Conservation Officer; TCO = Team Conservation Officer; PEIMA = Prince Edward Islands Management Authority.

Albatrosses and Petrels, and Convention on Wetlands of International Importance especially as Waterfowl Habitat [Ramsar Convention]); to create awareness of the value and fragility of island ecosystems; to support research that contributes to understanding human-induced changes; and to monitor the conservation and management of biota on the islands. These challenges will be met through the implementation of an integrated management system which addresses administration, conservation management, historical conservation and waste management as priority areas for action (table 2). The sections below outline the broad approach to addressing each management goal.

ADMINISTRATION

Logistics and environmental management

The plan makes recommendations regarding the institutional arrangements necessary to achieve effective and efficient management of the islands. The EMP places logistic and operational functions within the Department of Environmental Affairs and Tourism's Directorate of Antarctica and Islands, and environmental coordination and monitoring functions within the sister Directorate of Environmental Impact Management.

The Management Authority

Day-to-day management functions are the responsibility of the Prince Edward Islands Management Authority, which carries out its mandate using the structures and provisions of the EMP. The management authority is a semi-independent body, established by statutory provision, but outside direct control of the implementing structures of government, which reports to the Directorate of Environmental Impact Management. Its tasks include conservation and management of the islands, zoning, issuing permits and Protected Area Notices, evaluation of research proposals and products, implementing an environmental impact assessment procedure for the islands, establishing internal systems and soliciting advice from external parties (advisory committees), recording and reporting to the Minister of Environmental Affairs and Tourism on its deliberations and decisions, and conducting a comprehensive review and evaluation of the EMP every four years. The management authority is the final decision-making authority in most of these functions (e.g., permit administration and zoning, internal management, EMP review), but plays an advisory role in a few areas (e.g., adjudication of research proposals).

Personnel

The isolation of the Prince Edward Islands gives rise to special challenges in the staffing and day-to-day administration of the protected area. A permanent, full-time Senior Conservation Officer (SCO) position for the islands is now in place within the Directorate of Environmental Impact Management. The SCO is based on the mainland and is responsible for ensuring that the EMP is fully implemented. The SCO serves as an *ex officio* member and secretary of the Prince Edward Islands Management Authority, and the SCO or at least one suitably trained and deputised *ad hoc* Conservation Officer accompanies all voyages to the PEI. All other Conservation Officers report to the SCO.

A full-time Team Conservation Officer is appointed to the over-wintering team on Marion Island and is responsible for all conservation issues at the Prince Edward Islands during the over-wintering period, reporting directly to the SCO. The Team Conservation Officer will work closely with the

TABLE 2
Goals of the Prince Edward Islands Environmental Management Plan[1]

Administration
Limit and manage access to the Prince Edward Islands
Control and manage access to management zones within the Prince Edward Islands
Prevent any human impact on Prince Edward Island
Conservation management
Prevent the introduction of alien species and invasive species to the Prince Edward Islands
Control and/or eradicate alien and invasive species on the Prince Edward Islands
Prevent and control outbreaks of disease amongst birds and seals on and around the Prince Edward Islands
Protect and manage the biodiversity on and around the Prince Edward Islands through targeted multidisciplinary research
Prevent illegal and unsustainable collection, transport and importation of organisms and biological material from the Prince Edward Islands
Minimise disturbance of flora and fauna on and around the Prince Edward Islands during operation of craft (includes boats and helicopters)
Historical conservation
Protect and conserve the Prince Edward Islands' archaeological and palaeontological estate
Waste management
Implement appropriate and sustainable management of waste at the Prince Edward Islands

[1] In the EMP each goal is followed by the set of objectives, actions, targets and monitoring and remedial actions that is necessary to fully address it.

SCO and Team Leader to handle emergency situations, waste spills or disease outbreaks and contraventions of the EMP. The Construction Conservation Officer is responsible for ensuring that all construction activities on Marion Island are carried out in accordance with the EMP and any additional construction management plans. DEAT may appoint *ad hoc* Conservation Officers at any time to assist the SCO and the Team Conservation Officer in performing their duties during the annual relief voyage or any other construction, maintenance, emergency or replenishment visits.

Routine management

The primary goals of the management plan relating to administration of the islands are to control access to the islands and their five management zones, and to implement systems to prevent further human impacts on Prince Edward Island. Visits to the islands are controlled through a permit system, specifying which management zones visitors may enter and the activities they may undertake there. Secondary aims are to set out the reporting responsibilities of the management authority and its obligations for data collection and storage, and to establish a comprehensive capacity- building programme for the national Antarctic programme.

CONSERVATION MANAGEMENT

The conservation management goals of the Prince Edward Islands EMP centre on the prevention and management of biological invasions and disease outbreaks, minimisation of chemical and physical disturbance, protection of vertebrate populations of conservation significance on and around the islands, and prevention of illegal and unsustainable collection of organisms and biological material. A programme of targeted multidisciplinary research to address emerging conservation problems is proposed.

Prevention of and response to propagule transfer

Prevention of propagule transfer is centred on routes and vectors of transfer. The supply voyage of the vessel SA *Agulhas* is regarded as the principal route of transfer, while cargo, personnel and craft are major vectors. Propagule transfer is controlled through thorough cleaning, fumigation and regular inspection of the supply vessel and all its cargo prior to loading. Recommended practices for cargo packing in several locations are described, including the government stores, tertiary institutions and domestic settings. In addition, the EMP applies a measure of supply chain control to ensure that food and other products purchased for the islands are not contaminated at source or en route to the vessel.

The protection of Prince Edward Island is of paramount importance when alien introductions are considered. Marion Island has 13 alien vascular plant species, 25 alien invertebrate taxa (including an isopod, slug, and parasitic wasp species, at least one earthworm species, and several alien springtail and mite species; Chown *et al.* 2002; Lee *et al.* 2007) and one alien vertebrate species, the house mouse (*Mus musculus* Linnaeus, 1758; Jansen van Vuuren & Chown 2007), while domestic cats (*Felis catus* Linnaeus, 1758) have been eradicated (Bester *et al.* 2002). However, only three alien vascular plant species and, so far as is known, five alien invertebrate taxa occur on Prince Edward Island (Chown *et al.* 1998, Ryan *et al.* 2003, Hugo *et al.* 2006). Nonetheless, propagule transfer to Prince Edward Island is an ever-present risk given the regular, though infrequent, transfer of personnel and cargo to Prince Edward Island and the abundance of natural vectors between the islands. In response to this propagule pressure, the new EMP restricts the frequency of visits to Prince Edward Island to one expedition every second year by up to 10 people for a maximum of eight days, and requires that strict measures be applied to control access, quarantine, waste management and transport operations during these visits.

Aircraft are routinely deployed throughout Marion Island, and during every expedition to Prince Edward Island, providing a potential transport mechanism for propagules from either the mainland or the research base to other parts of the island group. To prevent such transfer to Prince Edward Island, the EMP requires that all air and water craft be thoroughly cleaned on board the supply vessel before being deployed on Prince Edward Island. These vehicles may not be operated directly between the two islands but must stop at the supply vessel as a quarantine measure. Outer gear used by personnel must be thoroughly cleaned on the mainland before issue, inspected on board the supply vessel during the "boot washing ceremony" and may not be used on both islands during a single expedition. Certain foodstuffs are prohibited from being taken onto Prince Edward Island.

Control of established alien species

The EMP recommends that the management authority lists and prioritises all alien species present on the islands, prepares an alien species management strategy and provides guidelines to differentiate between natural and human-mediated introductions to the islands. Control or eradication of the house mouse and several alien vascular plants on Marion Island will be necessary in the near future.

Historical conservation

The historical conservation policy of the PEI aims to record and preserve sites and objects which have cultural and/or historical significance. Although this policy applies to both islands in the group, neither island's historical sites and artefacts have been surveyed fully.

Management of the islands' archaeological and palaeontological estate is the responsibility of national and provincial heritage agencies. In general, artefacts remain *in situ* unless seriously threatened by continued exposure, in which case they are either stored in a small museum at the Marion Island research base or returned to the mainland. Collection of archaeological or palaeontological items is prohibited by law unless under permit from the relevant agencies, and private collections must be declared and their contents listed with the National Heritage Resources Agency (National Heritage Resources Act, No. 25 of 1999; Office of the President 1999).

WASTE MANAGEMENT

South African legislation and policy promote a "cradle to grave" approach to the management and treatment of waste, through all phases of the waste generation, handling and disposal life-cycle (Department of Environmental Affairs and Tourism 2000). In accordance with government policy, the Prince Edward Islands EMP aims to prevent and minimise waste generation and pollution at source, manage the impacts of unavoidable waste from generation to final disposal, and ensure that waste remains the responsibility of the agencies involved in its generation. Minimisation of waste generation and impact at the islands involves reducing the quantity of primary packaging on goods destined for the islands (where this is not in conflict with bio-sanitary practices), providing recycling and waste minimisation facilities on the islands and supply vessel, and using biodegradable and innocuous products whenever possible.

Waste handling practices on the islands are well developed already, but require refinement to ensure that waste is appropriately and safely separated, handled and stored. In general, the management plan recommends that waste be entered into the highest-level waste stream available using a hierarchical decision framework. For example, the waste generated on highly protected Prince Edward Island is entered into the waste stream of the transport and supply vessel; food, human and burnable waste is processed on the vessel and non-biodegradable, recyclable and hazardous waste is transferred into the mainland waste stream. Similarly, all waste (with the exception of grey water and sewage) generated away from base on Marion Island is stored and returned to base for entry into appropriate waste streams (table 3). As a result, very little waste disposal occurs away from base on Marion Island or on Prince Edward Island and waste is never transferred between islands due to the risk of disease or propagule transmission.

CONCLUSION

The draft Prince Edward Island EMP proposes a qualitative change in the way the islands are managed and conserved, and provides a level of detail that explicitly guides the management responsibilities of personnel based both on the islands and on the mainland. In other words, objectives are set, the actions required to address these objectives are laid out, the parties responsible for implementing these actions are identified, and remedial actions are explicitly set out in case of any failures in the primary chain from objective to implementing action.

The recently-promulgated National Environmental Management: Protected Areas Act specifies that management plans be drafted or updated for all national protected areas in South Africa. By law, such a management plan must be gazetted within three months of its acceptance by the Minister of Environmental Affairs and Tourism, whereupon it will become law. The EMP was delivered to DEAT in February 2006, and is in the process of being accepted.

TABLE 3
Waste management categories, treatment guidelines and destination waste streams for waste originating on Marion Island

Waste type	Treatment	Destination
Reusable and recyclable waste (metal containers and foil, glass, paper and cardboard, wood, plastic and polystyrene, composites, such as foil-lined milk and fruit juice cartons, non-medical waste-related ash from incinerator)	Washing/cleaning, separation into clearly marked containers	Mainland
Burnable waste (paper, cardboard, small pieces of wood and burnable medical waste, candle wax)	Separation of medical and non-medical waste	Incineration on Marion Island; ash entered into mainland waste stream
Environmentally hazardous biodegradable waste (waste water, human waste, food waste)	None at present (maceration and partial treatment in new base)	Outfall into ocean
Environmentally hazardous non-biodegradable waste (used oil including cooking oil, mechanical waste, batteries, laboratory, photographic and radiographic chemicals, light bulbs)	Principally, cleaning and separation into identified storage containers	Mainland
Bio-hazardous waste – food (uncooked fish, meat and all poultry waste, including eggs, chicken, melt water, bones, dried fruit stones and pips)	Freeze	Mainland
Bio-hazardous waste – non-food (medical sharps, bio-hazardous medical waste and ash from medical waste incineration)	Separation into identified storage containers	Mainland

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MANAGING FISHING IN THE SUB-ANTARCTIC

by D. G. M. Miller

(with seven text-figures and five tables)

Miller, D.G.M. 2007 (23:xi) : Managing fishing in the sub-Antarctic. *Papers and Proceedings of the Royal Society of Tasmania* **141**(1): 121–140. ISSN 0080-4703. CCAMLR Secretariat, P.O. Box 213, North Hobart, Tasmania, 7002 Australia*. Also: Institute for Antarctic and Southern Ocean Studies, University of Tasmania, Sandy Bay, Hobart, Tasmania 7005 Australia. *Address for correspondence.

Harvesting of finfish in the sub-Antarctic is briefly described together with an historical account of its management by the international Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) under the Convention of the same name (CAMLR Convention). The key objectives of the CAMLR Convention are outlined, with emphasis on the procedures adopted by CCAMLR to meet its management objectives through implementation of an ecosystem-based and precautionary approach. Four case studies are presented to illustrate CCAMLR's success as a modern-day and effective marine management organisation. The cases considered are CCAMLR's efforts to: (a) combat Illegal, Unreported and Unregulated (IUU) fishing, (b) mitigate incidental seabird bycatch during longline fishing for toothfish, (c) institute precautionary management of developing fisheries and (d) address environmental protection. In evaluating CCAMLR's actions, emphasis is given to the challenges faced and lessons learnt thereby highlighting the organisation's standing as an example of international best practice in the management of marine living resources on the high seas.

Key Words: CCAMLR management, ecosystem approach, precautionary approach, sub-Antarctic fisheries.

INTRODUCTION

In its 2006 estimate of global trends for marine fish stock exploitation, the Food and Agricultural Organisation of the United Nations (FAO 2007: 29) (see appendix 1 for acronyms used in this paper) indicated that:

> One-quarter of the stocks monitored was under-exploited or moderately exploited (3% and 20 % respectively) and could perhaps produce more. About half of the stocks (52%) were fully exploited and therefore producing catches that were at, close to, their maximum sustainable limits with no room for further expansion. The other one quarter were either overexploited, depleted or recovering from depletion (17%, 7% and 1% respectively) and thus were yielding less than maximum potential owing to excess fishing pressure exerted in the past, with no possibilities in the short to medium term of further expansion and with an increased risk of further declines and need for rebuilding.

The number of fully exploited marine fish stocks (fig. 1) exhibited a consistent and decreasing trend between 1974 and 2006, while the number of under-exploited, or moderately exploited stocks, also declined over the same period. By contrast, the proportion of over-exploited and depleted stocks steadily rose from about 10% in the mid-1970s to nearly 25% in 2006.

Such trends have not only resulted in ever-increasing efforts to locate new stocks for exploitation, they have also heightened concerns that unsustainable fishing practices may exert too heavy a price on marine ecosystem productivity as a whole (Pauly *et al.* 2002). Predominantly negative, this price includes habitat degradation, excessive bycatch, discarding of unwanted catches and ecological consequences that include environmental degradation as well as other harmful effects of harvesting activities. Consequently, Cochrane & Doulman (2005) conclude that unsustainable fishing practices are the end product of a widespread failure in fisheries management to effectively balance biological and ecological sustainability with socio-economic objectives or expectations.

In the two decades prior to the 1982 negotiation of the United Nations Convention on the Law of the Sea ("LOS Convention"), the international community strove to develop an international legal framework addressing over-exploitation of living marine resources. A major aim of this process was to maintain the health of the ecosystems in which such resources occur (Cochrane & Doulman 2005). With the LOS Convention's finalisation, impetus and purpose were given to negotiating associated international legal instruments (table 1), particularly to give effect to declarations from the 1992 United Nations Conference on Environment and Development (UNCED), and more recently the 2002 World Summit on Sustainable Development (WSSD).

The legal instruments summarised in table 1 address a wide range of fisheries-related issues. These include biological considerations, conservation concerns, and application of both a precautionary and ecosystem-based (EAF) approach to fisheries management (Cochrane & Doulman 2005). In particular, the 1995 United Nations Fish Stocks Agreement (UNFSA) (United Nations 1998: 7–37) broadens fisheries management objectives to include mitigation of negative impacts on the marine environment, preservation of marine diversity and maintenance of key marine ecosystem qualities (Edeson *et al.* 2001).

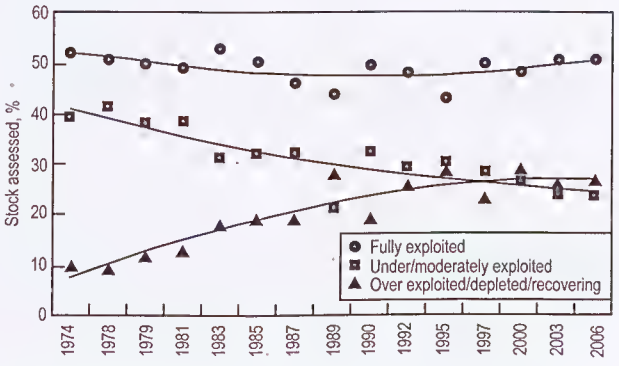

FIG. 1 — Global trends in the state of world marine stocks for the period 1974 to 2006 (after fig. 19 in FAO 2007).

TABLE 1
Some key international agreements directly impacting national and international management of marine living resource exploitation (after Cochrane & Doulman 2005)

Agreement name	Entry into force	Purpose	Legal standing	No. parties	Comments
Marine Agreements					
1982 United Nations Convention on the Law of the Sea (LOS Convention)	16/11/2004	Primary legal framework for international governance of oceans. Addresses ocean use. Legal basis for conservation, management & research of marine living resources (Aqorau 2003).	Legally binding instrument	152	Reference point for all fisheries agreements negotiated subsequently
1993 FAO Agreement to Promote Compliance with Management Measures by Fishing Vessels on the High Seas (FAO Compliance Agreement)	24/4/2003	Better control of fishing vessels on high seas (including mandating authorization to fish) by strengthening "flag-State responsibility"	Legally binding instrument	29	Ensure flag vessels do not undermine effective international conservation & management measures. Limits opportunities for vessels with bad compliance records to "re-flag" & avoid regulation of their fishing activities
1995 FAO Code of Conduct for Responsible Fisheries (Code of Conduct)	31/10/1995 (adopted)	Guidelines consistent with relevant international law, to promote responsible fishing & fisheries activities & account for relevant biological, technological, economic, social, environmental & commercial aspects	Voluntary instrument	–	Covers all fisheries aspects (i.e., aqua-culture, exploration, planning & post-harvest practice/ trade). Has four International Plans of Action Attached -Sharks, IUU Fishing, Fishing Capacity & Incidental Seabird Mortality
1995 United Nations Agreement for the Implementation of the United Nations Law of the Sea of 10 December 1982 Relating to the Conservation of Straddling Stocks and Highly Migrating Fish Stocks (UN Fish Stocks Agreement – UNFSA)	11/12/2001	Effective implementation of LOS Convention to prevent overexploitation of high-seas fish stocks (notably highly migratory & straddling stocks)	Legally binding instrument	62	Advocates holistic fisheries management to address marine environ-ment & ecosystem con-siderations, application of precaution & marine biodiversity preservation
2001 Reykjavik Declaration on Responsible Fisheries in the Marine Ecosystem	4/10/2001 (Drafted)	Work collectively towards developing guidelines to incorporate ecosystem considerations into fisheries management	Non-legally binding instrument	–	Requested FAO draft EAF guidelines - produced in 2003 (FAO 2003)
Related Agreements					
1975 Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)	1/7/1975	Ensure international trade in specimens of wild animals & plants does not endanger their survival	Legally binding instrument	169	MOU of 3/10/2006 between FAO & CITES to consult on scientific, legal & technical matters for CITES Appendices Listing of exploited aquatic species
1992 Convention on Biological Diversity (CBD)	29/12/1993	Sustainable development by conserving biodiversity, sustainable use of bio-diversity & equitable sharing of genetic resources	Legally binding instrument	189	Translates Agenda 21 principles. 1995 Jakarta Mandate focuses on integrated management of sustainable marine & coastal areas/species use.
Agenda 21 of 1992 UN Conference on Environment and Development (UNCED)	–	Programme of action for sustainable development	Voluntary agreement	–	Agenda 21 Chapter 17 deals with protection of ocean, all seas, coastal areas & their living resources. Promotes implementation 1982 LOS Convention & adoption precautionary approach. CBD was concluded at UNCED.
2002 Plan of Implementation of World Summit on Sustainable Development (WSSD Plan of Implementation)	–	Update & reinforcement of UNCED action programme	Voluntary agreement		Consolidates & reinforces implementation of existing fisheries-related instruments. Sets deadlines (where possible) no later than 2015 for EAF application & fish stock maintenance at MSY

From an ecosystem perspective, the major challenge to implementing such legally binding and voluntary, or non-binding, instruments is to balance ecosystem sustainability with human socio-economic expectation through effective marine living resource management. As indicated by the FAO (2003: 14):

> The purpose of an ecosystem approach to fisheries is to plan, develop and manage fisheries in a manner that addresses the multiple needs and desires of societies, without jeopardizing the options for future generations to benefit from the full range of goods and services provided by marine ecosystems.

This suggests that the only way to promote food security is through sustainable marine living resource use and the optimisation of ecological, social and economic benefits for current and future generations.

There is little doubt that the scope and potential impact of the various instruments identified in table 1 are profound. However, there are irrefutable challenges to their effective implementation. As Cochrane & Doulman (2005) assert, many countries appear to be experiencing "instrument implementation fatigue" and this does not bode well for some, if not many, of the key sustainability objectives for effective marine living resource management being met.

Nonetheless, many such considerations have been addressed effectively by the 1980 Convention on the Conservation of Antarctic Marine Living Resources (CAMLR Convention) (CCAMLR 2007) and its attached executive Commission (CCAMLR) nearly a decade and a half before the UNFSA's existence. In fact, implementation of the CAMLR Convention foreshadowed many international advances in fisheries management worldwide during that time and continues to do so (Miller *et al.* 2004).

This paper outlines how effectively CCAMLR has implemented the CAMLR Convention's ecosystem and precautionary-based management approach in the sub-Antarctic over the past 25 years. The Convention's entry into force is briefly described and a brief history of finfish fisheries in the sub-Antarctic (north of 60°S) portion of the CCAMLR Area is provided. Examples of various initiatives are used to outline how CCAMLR has gone about its work. Attention is given to the attached administrative processes as well as perceived successes and/or failures. The four case studies show how CCAMLR has addressed Illegal, Unreported and Unregulated (IUU) (see paragraph 3 of FAO 2001 for definition) fishing in the Convention Area, incidental mortality of seabirds during longline fishing, precautionary management of fisheries (particularly for *Dissostichus eleginoides* (Gill & Townsend, 1901) - Patagonian Toothfish; "Toothfish") during harvest development, and environmental protection as an element of the organisation's EAF. The outcomes are used to illustrate how CCAMLR has come to perceive its future needs and what has been learned from its past practices. The opinions expressed should be taken as those of the author and do not reflect the collective or official views of CCAMLR.

THE CAMLR CONVENTION

Much has been written about CCAMLR (e.g., Miller *et al.* 2004) and it is not intended to provide full details of the organisation's history here. However, a few key features of the CAMLR Convention are worth highlighting.

Following negotiations by the Consultative Parties to the 1959 Antarctic Treaty, the CAMLR Convention entered into force on 7 April 1982. Its basic objective may be summarised as:

> Conserving, including rational use of, Antarctic marine living resources south of the Antarctic Polar Front (c. 45°S) through precautionary and ecosystem-based management.

The management and conservation principles outlined in Article II of the Convention were without international precedent (Anon. 2002, Miller *et al.* 2004). They mandate that harvesting and associated activities should be carried out in the CCAMLR Area with due commitment to the following operational considerations:

- Conservation and rational (i.e., sustainable) resource use should be balanced.
- Target species status should be maintained to ensure stable recruitment and stock levels close to greatest net annual biological yield.
- Direct and indirect effects of harvesting should be addressed.
- Ecological relationships between target, dependent and related species should be maintained.
- Depleted populations should be restored.
- Risks of ecosystem changes, not irreversible in 20 to 30 years, should be minimized.
- Management action should take into account anthropogenic effects and environmental change(s).

The balancing of "conservation" and "rational use" in Article II is clearly aimed at ensuring that existing ecological relationships between harvested, dependent and related species are maintained, and that depleted populations are restored to levels at which their biological productivity is greatest. However, the term "rational use" may have various interpretations, especially when an ecological, as opposed to an economic, perspective is assumed. For this reason, CCAMLR has developed a working definition for the term with, *inter alia*, it being considered to imply that: (a) harvesting of resources is on a sustainable basis and (b) harvesting on a sustainable basis means that harvesting is conducted to ensure that the highest possible long-term yield from the resource, subject to the general conservation principles outlined in paragraph 3 of Convention Article II (CCAMLR 1988 paragraph 139).

Since the CAMLR Convention's entry into force, the ecosystem and precautionary approaches outlined in Article II have both directed and challenged CCAMLR's conservation efforts (Constable *et al.* 2000, Miller 2000) in the CCAMLR Area. The ecological uncertainties associated with effectively, and fully, implementing the Convention's provisions have necessitated innovative thinking to develop an holistic, scientific and ecologically-based approach to regulating the marine living resources affected by harvesting.

These features distinguish the CAMLR Convention's focus from more customary approaches to fisheries management, such as those based on maximum sustainable yield (MSY) (Butterworth 1986). However, limited knowledge of harvested stock dynamics (especially for Antarctic Krill – *Euphausia superba* Dana, 1852), as well as equally limited knowledge of functional relationship(s) between harvested and other species (i.e., birds, seals and whales), has tended to impede practical implementation of Article II (Constable 2002). Nevertheless, as shown below, considerable progress has been made and CCAMLR is pre-eminent as an implementable, effective, modern, international fisheries and conservation instrument (Constable *et al.* 2000).

The need for supportive science implicit in Article II of the CAMLR Convention, along with an outline of the type of research required, is more explicitly developed in Articles V, VI, VIII and IX. Moreover, Article IX identifies possible management measures (termed "conservation measures" – CM) to be applied in meeting Article II objectives. In turn, CM are required to be based on the best scientific evidence available (Article IX, paragraph 1.(f)) and include, *inter alia*, setting of catch limits, effort controls, closed areas/seasons etc.

The ecological considerations in the CAMLR Convention's Preamble result in Article I confining CCAMLR's area of operation to south of the Antarctic Convergence (Antarctic Polar Front) (fig. 2). The Front is perceived as a biogeographic boundary to the species assemblages confined therein (Miller 2000). With the close connection between the CAMLR Convention and the Treaty, the CCAMLR boundary effectively extends the Antarctic Treaty's area of influence north of 60°S, (i.e., from the continental boundary to the Polar Front) (Anon. 2002). As a consequence, the Convention is required to deal with the legal and jurisdictional implication associated with application of national sovereignty over certain sub-Antarctic islands. While the relevant provisions "freezing" sovereign claims in the Antarctic Treaty Area are addressed in CAMLR Convention Articles III–V, it was necessary to attach a Statement by the Chairman of the Conference on the Conservation of Antarctic Marine Living Resources (Chairman's Statement) to address sovereignty considerations farther north (Miller *et al.* 2004).

CCAMLR SUB-ANTARCTIC FISHERIES

Fishing in the CCAMLR Area has predominantly targeted finfish and Antarctic krill (Miller 1991), with finfish harvesting dating from the turn of the last century. Between 1901 and 1903, whalers discovered large concentrations of marbled rockcod (*Notothenia rossii* Richardson, 1844) around the sub-Antarctic island of South Georgia. For various economic reasons, most notably remoteness from potential markets and greater interest in whaling, this fishery was not fully realised at the time. Subsequent exploratory fishing by Argentina, Norway and Japan between 1930 and 1960 also failed (Miller 1991). The further development, course and fate of finfish fisheries in the CCAMLR Area are described in a number of papers (e.g., Kock 1992, Williams 1995, Williams & de la Mare 1995, Agnew & Nicol 1996, de la Mare *et al.* 1998).

Large-scale harvesting of finfish commenced in 1969/70 in the Southwest Atlantic around South Georgia (CCAMLR Statistical Subarea 48.3) and the following season in the Indian Ocean at the Kerguelen Islands (CCAMLR Statistical Division 58.5.1). The former Soviet Union was heavily involved in both these fisheries until declaration of a 200-mile Exclusive Economic Zone (EEZ) around the Kerguelen Islands largely forced Soviet vessels out of that fishery post-1980. Bottom trawling for Toothfish at the Kerguelen Islands continued until the mid-1990s (Duhamel 1993).

Finfish harvesting at South Georgia expanded southward to the South Orkney Islands (CCAMLR Statistical Subarea 48.2) in 1977/78. These more southerly grounds yielded moderate catches for only a few years and by the early 1980s were no longer commercially viable (Miller 2000).

Until about 1985, all finfish harvesting in the sub-Antarctic was by trawlers undertaking commercial fishing and was mainly confined to Southern Ocean island shelves (Kock *et al.* 1985). Since then, finfish harvesting has been more widespread in various CCAMLR Statistical Areas, Subareas and Divisions (table 2, fig. 2).

In the sub-Antarctic *per se*, historic catches (Kock 1992, 2001) targeted relatively few species in the locations identified in figure 2. As outlined in Fischer & Hureau (1985), the most notable of these included *N. rossii*, Toothfish, Antarctic Toothfish (*Dissostichus mawsoni* Norman, 1937) and Mackerel Icefish (*Champsocephalus gunnari* Lönnberg, 1905). Minor catches were also taken of South Georgia Icefish (*Pseudochaenichthys georgianus* Norman, 1937), Unicorn Icefish (*Channichthys rhinoceratus* Richardson, 1844), Blackfin Icefish (*Chaenocephalus aceratus* Lönnberg, 1906), Humped Rockcod (*Lepidonotothen* [*Notothenia*]

TABLE 2
CCAMLR Statistical Areas, Subareas and Divisions where finfish (by species) harvesting has occurred

Location	Common name	Species fished
FAO Statistical Area 48	*Atlantic Ocean Sector*	
Subarea 48.1	South Shetlands	*Notothenia rossii, Chaenocephalus aceratus, Chaenodraco wilsoni, Champsocephalus gunnari, Lepidonotothen* [*Notothenia*] *gibberifrons*
Subarea 48.2	South Orkneys	*N. rossii, C. aceratus, C. gunnari, Pseudochaenichthys georgianus, Dissostichus eleginoides, L. gibberifrons, Lepidonotothen* [*Notothenia*] *squamifrons*
Subarea 48.3	South Georgia	*N. rossii, D. eleginoides, C. gunnari, Electrona carlsbergi, C. aceratus, P. georgianus, N. gibberifrons, N. squamifrons, Patagonotothen guntheri*
Subarea 48.4	South Sandwich	*D. eleginoides*
FAO Statistical Area 58	*Indian Ocean Sector*	
Subarea 58.6	Crozet & Prince Edward	*D. eleginoides*
Subarea 58.7	Prince Edward	*D. eleginoides*
Subarea 58.4.2		*C. wilsoni, Dissostichus mawsoni*
Division 58.4.3	BANZARE & Elan Banks	*D. eleginoides D. mawsoni*
Division 58.4.4	Ob & Lena Banks	*D. eleginoides, L. squamifrons*
Division 58.5.1	I. Kerguelen	*N. rossii, D. eleginoides, C. gunnari, L. squamifrons*
Division 58.5.2	Heard & Macquarie	*D. eleginoides, C. gunnari*

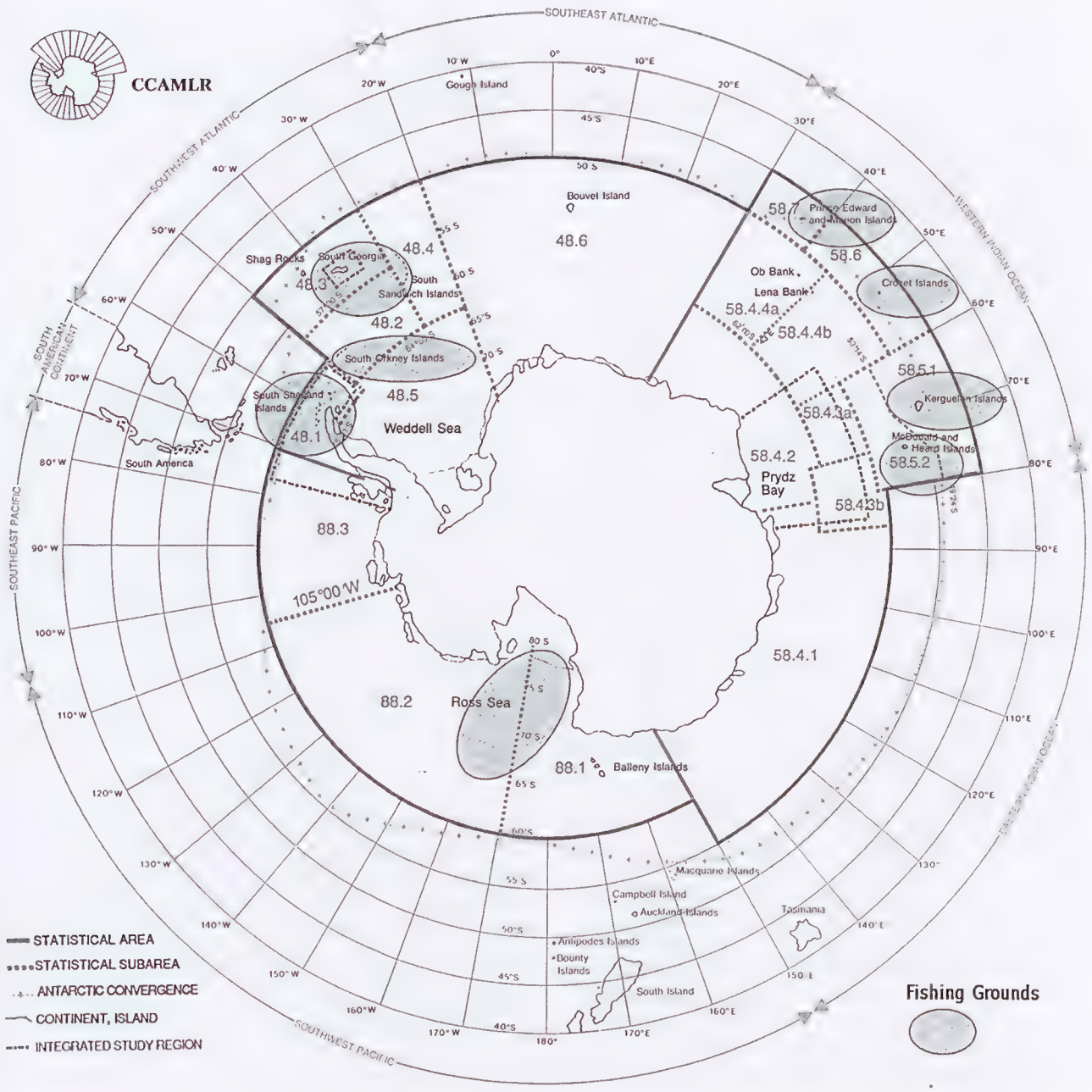

*FIG. 2 — The CCAMLR Area (modified from CCAMLR 1997–2006). The location of finfish fishing grounds in the CCAMLR Area are shown, with fishing on Antarctic Toothfish (*Dissostichus mawsoni*) in CCAMLR Statistical Subareas 88.1 and 88.2 included for completeness.*

gibberifrons Lönnberg, 1905), Grey Notothenia or Rockcod (*Lepidonotothen* [*Notothenia*] *squamifrons* Günther, 1880), Günther's Notothenia (*Patagonotothen guntheri* Norman, 1937), Subantarctic Lanternfish (usually identified as *Electorna carlsbergi* Tåning, 1932) and the Spiny Icefish (*Chaenodraco wilsoni* Regan, 1914). From time to time, bycatch included *G. gibberifrons*, various icefish species (family Channichthyidae), skates/rays (*Raja georgiana* Norman, 1938, *Bathyraja* spp. and *Macourus* spp.), and in recent years sharks (*Somniosus* spp.).

Prior to the CAMLR Convention, finfish harvesting in the CCAMLR Area was largely a "boom and bust" affair, similar to Antarctic whaling (Miller 2000). This entailed the successive discovery, exploitation and depletion of each new target stock over progressively shorter time scales. During the late 1970s and early 1980s, the severe depletion of demersal fish stocks (most notably *N. rossii*) was followed in the second half of the latter decade by harvesting of benthopelagic species such as Toothfish, species with variable year class strengths (*C. gunnari*) and mesopelagic species such as *E. carlsbergi*.

By the early 1990s, CCAMLR CM prohibited directed fishing on most finfish species (e.g., *N. rossii* in particular) or had introduced total allowable catches based on some objective assessment of stock yield (Constable *et al.* 2000). Other management measures were also introduced and included, *inter alia*, closed areas/seasons as well as measures to regulate new and exploratory fisheries.

Both the South Orkneys (Subarea 48.2) and Antarctic Peninsula (Subarea 48.1) were closed to directed finfish harvesting in 1993. Economic considerations effectively ended the *E. carlsbergi* fishery at the end of the 1991/92

season (Miller 2000) while other fishing grounds, such as the Ob and Lena Seamounts, were effectively closed from the mid-1990s onwards.

Two other major developments characterised the finfish harvest in the CCAMLR Area. During the 1988/89 season, the former Soviet Union introduced a deepwater longline fishery for Toothfish around South Georgia (Subarea 48.3) (CCAMLR 1989 paragraph 104). Previously, the species had predominantly been taken as by-catch in various trawl fisheries; a point well-illustrated by the 4200- and 8300-tonne longline catches in 1988/89 and 1989/90 respectively compared with the 5000-tonne accumulated catch over the previous ten years (1977 to 1988). The development of this longline fishery triggered the emergence of a substantial Toothfish IUU fishery.

Between 1972/73 and 2005/06, a total of 3.66 million tonnes of finfish were taken in the sub-Antarctic portion of the CCAMLR Area (CCAMLR 1990–2006). Of this total, about 2.16 million tonnes were taken in the West Atlantic (Area 48), with 1.83 million tonnes (85%) caught around South Georgia (Subarea 48.3). Of the 1.5 million tonnes caught between 1969/70 and 2005/06 in the Indian Ocean, 0.83 million tonnes (55%) are attributable to the Kerguelen Islands environs (Division 58.5.1).

CCAMLR MANAGEMENT PROCESS

The functions of many regional management organisations rely on the effective administration and synchronisation of some key institutional elements. In CCAMLR's case, these elements comprise CCAMLR itself, Contracting Parties, the Scientific Committee, other subsidiary bodies and the Secretariat.

Commission

Various CAMLR Convention Articles outline the conditions for becoming a Commission Member (Article VII), CCAMLR's legal character (Article VIII), its various functions and associated matters (Articles IX–XI), and the attached conditions for consensus-based decision-making (Article XII).

In outlining conditions for CCAMLR membership, Article VII.(2) distinguishes between Contracting Parties to the CAMLR Convention and Members of the Commission. For the latter, only founding Contracting Parties were immediately eligible for Commission membership (Article VII.(2).(a)). Parties acceding to the Convention pursuant to Article XXIX are entitled to become Commission Members while engaged in active research on, or harvesting of, the marine living resources to which the Convention applies (Article VII.(2).(b)).

Under Article IX, CCAMLR is politically "responsible" for giving effect to the CAMLR Convention's objective and principles set out in Article II. This is achieved by facilitating relevant research and by promulgating CM, with Article IX.(2) identifying the substance of the latter. Decision-making on CM and other matters of substance is by consensus (Article XII) and limited to Commission Members only (i.e., those parties that have met the requirements of Article VII.(2)). Article IX.(6) sets the conditions for CM implementation.

The application of CM in waters over which the existence of state sovereignty is recognised by all Contracting Parties is qualified by the Chairman's Statement (see above). The procedures for applying national measures as opposed to CCAMLR-agreed CM are set out in paragraph 3 of this Statement.

Finally, key emphasis is placed on, and guidance given to, CCAMLR co-operation with other relevant international organisations, both inter-governmental and non-governmental (Article XXIII).

Contracting Parties

Contracting Party and Member responsibilities are outlined in Articles XXI and XXII. Together with national responsibilities for implementing CM (Article XXI.(1)), Contracting Parties are mandated to cooperate in establishing a system of observation and inspection to promote the CAMLR Convention's objective and to ensure that its provisions are met (Article XXIV). This requirement and the annually published list of CM in force (i.e., CCAMLR 1997–2006) lay the foundation for the monitoring, control and surveillance (MCS) system through which CCAMLR regulates relevant activities in the CCAMLR Area. Over the years, the CM themselves have evolved to provide essential interpretive and administrative elements for the execution of Contracting Party responsibilities.

Scientific Committee

The Scientific Committee, established by CAMLR Convention Article XIV, serves to provide the Commission with the best scientific information available (Article IX.(1).(f)) for the latter's work. The Committee's membership is limited to Commission Members (Article XIV.(2)) and it serves as a forum for consultation and cooperation in the collection, study and exchange of relevant information to promote scientific research (Article XV.(a)). Its activities are outlined in Article XV.(2) and include regular assessment of stock status and trends, analyses of harvesting effects, both direct and indirect, and the provision of such assessments, analyses etc. to the Commission as required.

Other subsidiary bodies

CCAMLR relies on input from two other standing committees established under Rule 36 of its Rules of Procedure. The Standing Committee for Implementation and Compliance (SCIC) develops advice on MCS, compliance enforcement and application of the Observation Scheme and Inspection System. The Standing Committee on Administration and Finance (SCAF) provides advice on general administrative (e.g., functioning of the Secretariat) and budgetary (as per Article XIX as well as the Commission's Financial and Staff Regulations) (CCAMLR 2007 – Footnote 2) matters.

Various specialist scientific Working Groups have been established under Article XVI.(3) and Scientific Committee Rule of Procedure 13. These are essentially forums for expert consultation and detailed scientific debate. The most notable groups currently include the Working Group for Fish Stock Assessment (WG-FSA), the Working Group for Ecosystem Monitoring and Management (WG-EMM),

the Working Group on Assessment Methods (WG-SAM) and the *ad hoc* Working Group on Incidental Mortality Associated with Fishing (WG-IMAF). All undertake routine analyses required by the Scientific Committee and serve as the first step in preparing appropriate advice for the Commission's consideration and to inform its decision-making processes.

The Secretariat

Finally, in establishing its headquarters in Hobart, Australia, (Article XIII) and the post of Executive Secretary (Article XVII), the CAMLR Convention provides for the day-to-day administration of CCAMLR. Under the Executive Secretary's leadership, the Secretariat archives data submitted by the Contracting Parties and circulates relevant information amongst the Parties. It also publishes and translates documents related to the Commission's work (table 3) while undertaking various other functions as directed by CCAMLR. In conformity with Article XIII.(3), the Secretariat now serves as the venue for CCAMLR annual meetings.

Over the past 25 years, CCAMLR has evolved an annual cycle for its essential business. As illustrated in figure 3, the key outputs from this process comprise fishery regulations in the form of CM and depend on each administrative component outlined above operating effectively. CCAMLR's annual, iterative and progressive nature has meant that outputs have become more complicated and sophisticated over time, a point illustrated by the breadth, and subject depth, of CM both past and present.

Consistent with the objectives of Article II of the CAMLR Convention, CM adopted by CCAMLR to date have been directed at both fisheries regulation (table 4) and environmental protection (table 5). As such, the unique status and international trend-setting nature of the following CCAMLR CM and resolutions are particularly noteworthy, along with the issues that they strive to address. These include:

- incidental mortality of birds and mammals during fishing (CM 25-02 and 25-036 – table 4, R 22/XXV; table 5)
- notification and procedures aimed at regulating new and exploratory fisheries in the absence of information (CM 21-01 and 21-02; table 4)
- Contracting Party, including nationals, compliance (CM 10-06 and 10-08;– table 4)
- Non-Contracting Parties compliance and cooperation enhancement (CM 10-07, R 14/XIX, 19/XXI, 24/XXIV and 25/XXV; table 4)
- general environmental protection (CM 22-04, 22-05, 26-01, 32-09 and 32-18; table 5).

The CCAMLR achievements most worth noting have been the Catch Documentation Scheme (CM 10-05) (Sabourenkov & Miller 2004) to monitor trade in IUU-caught Toothfish, along with CM addressing fisheries notification, authorisation and at-sea monitoring procedures (CM 10-02, 21-01, 21-02 and 10-04) (Miller *et al.* 2004). General environmental protection measures (particularly CM 26-01 and 22-05) have also been significant. The amalgamation of good environmental practice for fishing vessels into a single measure (CM 26-10) is revolutionary while an interim prohibition on bottom trawling (CM 22-05) is both significant and pre-emptive.

The successful implementation of such measures does much to counter the criticism that CCAMLR's consensus-based decision-making is too slow. They also provide clear justification for the organisation being recognised as the pre-eminent leader in the world of fisheries management (Small 2005); a status that is largely attributable to the scope, effect and innovation of CCAMLR's management approach and mandate implementation (Miller *et al.* 2004, Willock & Lack 2006).

CCAMLR CASE STUDIES

Four case studies are reviewed here to illustrate some of CCAMLR's major achievements in setting up a management approach consistent with the principles and objectives outlined in Article II of the Convention.

TABLE 3
CCAMLR annual publications

Publication	Frequency	Medium	Language	Nature
Commission Report	Annual	Hardcopy Web copy	English, French, Russian, Spanish	Meeting Report Commission & subsidiary bodies
Scientific Committee Report	Annual	Hardcopy Web copy	English, French, Russian, Spanish	Meeting Report Scientific Committee & subsidiary bodies
Schedule of Conservation Measures in Force	Annual	Hardcopy Web copy	English, French Russian, Spanish	Texts Binding CM & Non-Binding Resolutions in Force
Statistical Bulletin	Annual	Hardcopy Web copy	English, French, Russian, Spanish	Aggregated Fisheries Statistics
CCAMLR Science	Annual	Hardcopy Web copy	English	Scientific journal

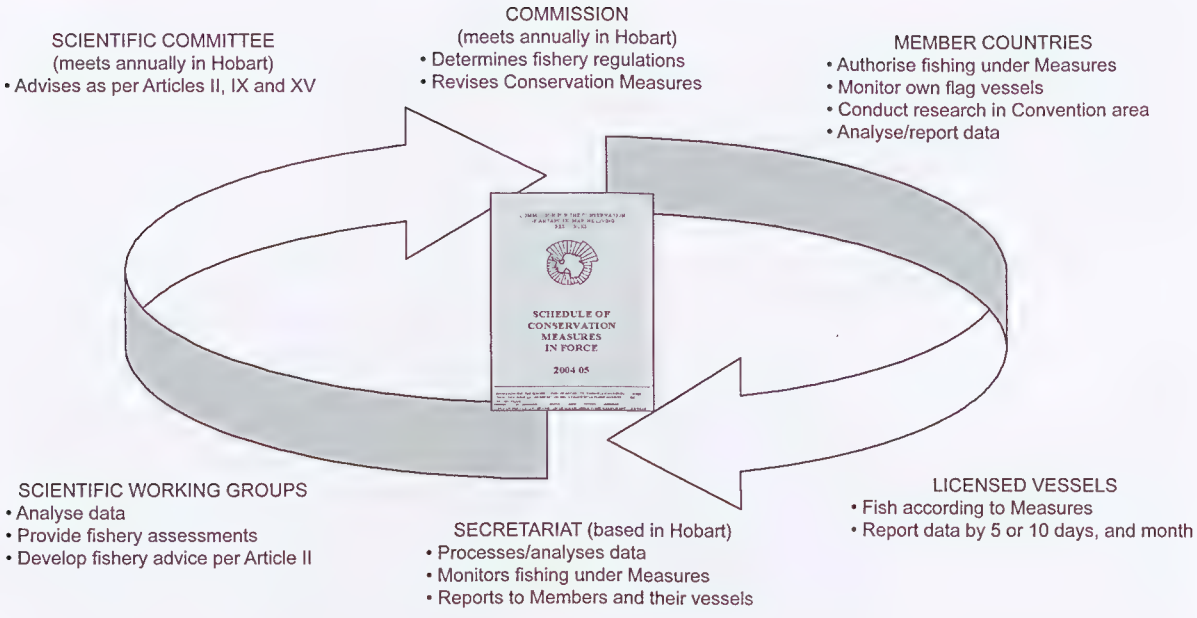
SCIENTIFIC COMMITTEE
(meets annually in Hobart)
• Advises as per Articles II, IX and XV
COMMISSION
(meets annually in Hobart)
• Determines fishery regulations
• Revises Conservation Measures
MEMBER COUNTRIES
• Authorise fishing under Measures
• Monitor own flag vessels
• Conduct research in Convention area
• Analyse/report data
SCHEDULE OF CONSERVATION MEASURES IN FORCE
2004 05
SCIENTIFIC WORKING GROUPS
• Analyse data
• Provide fishery assessments
• Develop fishery advice per Article II
SECRETARIAT (based in Hobart)
• Processes/analyses data
• Monitors fishing under Measures
• Reports to Members and their vessels
LICENSED VESSELS
• Fish according to Measures
• Report data by 5 or 10 days, and month

FIG. 3 — Annual cycle of CCAMLR management and associated actions (see text for details).

TABLE 4
Some CCAMLR regulatory Conservation Measures (CM) and Resolutions (R) (CCAMLR 1997–2006)

Type of measure	Measure
Fishery Regulatory Measures	
Prohibit directed Toothfish fishing in absence CM	CM 32-09
Advance notification of new fisheries.	CM 21-01
Advance notification & conduct of exploratory Toothfish fisheries, including data collection & research plans	CM 21-02, 41-01
Fishing effort limitation	CM 41-04 to 41-07
Reporting catch, effort & biological data, including reporting of fine-scale data	CM 23-01, 23-02, 23-03, 23-04 & 23-05
Placing international scientific observers on vessels targeting Toothfish	CM 41-01 & others Scientific Observer Scheme
Reducing seabird mortality during longline & trawl fishing	CM 25-02, 25-03
Flag State Measures	
Contracting Party licensing & inspection obligations for fishing vessels under their flag in Convention Area	CM 10-02
At-sea inspections of Contracting Party fishing vessels	System of Inspection
Marking of fishing vessels & fishing gear	CM 10-01
Deployment satellite-based VMS on vessels (except krill fishery) licensed by CCAMLR Members to fish in Convention Area	CM 10-04
Toothfish Catch Documentation Scheme	CM 10-05
Port State Measures	
Port inspections vessels landing Toothfish to ensure compliance CCAMLR CM	CM 10-03
Scheme promoting compliance by Contracting Party vessels with CM	CM 10-06
Scheme promoting compliance by Non-Contracting Party vessels with CM	CM 10-07
Scheme promoting compliance by Contracting Party nationals with CM	CM 10-08
Resolutions	
Harvesting stocks occurring both within, & outside, Convention Area, with due respect to CCAMLR CM	R 10/XII
Implementation Catch Documentation Scheme by Acceding States & Non-Contracting Parties	R 14/XIX
Use of ports not implementing Toothfish Catch Documentation Scheme	R 15/XIX
Application of VMS in Catch Documentation Scheme	R 16/XIX
Use of VMS & other measures to verify CDS catch data outside Convention Area, especially in FAO Statistical Area 51	R 17/XX
Harvesting of Toothfish outside areas of Coastal State jurisdiction adjacent to Convention Area in FAO Statistical Areas 51 & 57	R 18/XXI
Flags of non-compliance	R 19/XXI
Electronic Catch Documentation Scheme for Dissostichus eleginoides	R 21/XXIII
Non-Contracting Party Cooperation Enhancement Program	R 24/XXIV
Combating IUU fishing in Convention Area by Non-Contracting Party flag vessels	R 25/XXV

TABLE 5
Some CCAMLR environmental protection Conservation Measures (CM) and Resolutions (R)

Type of measure	Measure
General Environmental Protection	
Interim prohibition of deep-sea gillnetting	CM 22-04
Interim restrictions on bottom trawling gear use in high seas areas within Convention Area, 2006/07 to 2007/08	CM 22-05
General environmental protection during fishing	CM 26-01
Area Closure/Protection	
Areas closed to directed fishing for Finfish in Subareas 48.1, 48.2	CM 32-02, 32-03
Areas closed to directed fishing except under specific CM	CM 32-09
Fishing Season	
Definition	32-01
Limit fishing to specific fishing seasons	CM 41-02.(5)*, 41-03.(6), 41-04.(3), 41-05.(4), 41-06.(3), 41-07.(3), 41-08.(3), 41-09.(3). 41-10.(3)/(4), 41-11.(4), 42-01.(5), 42-02.(6), 51-01.(5), 51-02.(4), 51-03.(2) & 52-01.(6)
Site Protection	
Procedures for, & protection of, CEMP (CCAMLR Ecosystem Monitoring Programme) Sites	CM 91-01 to 91-03
Species Protection	
Prohibition of directed fishing for certain species	CM 32-04 to 32-17
Shark conservation	CM 32-18
Incidental mortality mitigation	CM 25-02, 25-03 & relevant section of numerous fishery regulation CM
Bycatch regulation	CM 33-01, 33-02, 33-03, 41-01.(4), 41-02.(6-8), 41-05.(7), 41-06.(4), 41-07.(4),41-08.(4) 41-11.(7), 42-01.(6), 42-02.(7) & 52-01.(7)
International Cooperation	
Incidental actions to reduce seabird incidental mortality arising from fishing	R 22/XXV
Fishing Gear Regulation	
Marking of fishing vessels & gear	CM 10-01
Mesh size regulation	CM 22-01, 22-02 & 22.03
Fishing gear weighting, construction & operation	CM 25-02.(2), 25-02.(3), 25-03.(6) & 25-03.(5)
Fishing gear testing	CM 24-02 & 24-03
Maritime Safety	
Minimum safe vessel lights during night longlining	CM 25-02.(4) & 25-03.(2)
Safety on board vessels fishing in CCAMLR Area	R 23/XXIII
Ice-strengthening standards in high-latitude fisheries	R 20/XXII

* References in parentheses are to specific CM paragraphs (CCAMLR 1997–2006)

Combating IUU fishing

Undoubtedly, IUU fishing poses a serious challenge to effective ocean governance and hence continues to preoccupy a number of important international forums such as the FAO (FAO 2001), the Committee for Fisheries (COFI) (COFI 2005) and the recent Inter-Ministerial Task Force on IUU Fishing (HSTF 2006). In its broadest implications, IUU fishing not only compromises stock sustainability, but also undermines food security and serves to deny economic advancement (MRAG 2005).

CCAMLR has always recognised that compliance enforcement poses a serious challenge to the effective implementation of its CM. The problem is compounded by the Convention's area size, (35 million km^2), remoteness and open access, particularly in respect of the high seas (Molenaar 2001). These concerns, together with growing interest in economically valuable Toothfish stocks during the early to mid-1990s, meant that CCAMLR was forced to face the challenge posed by IUU fishing as a matter of priority.

Until the emergence of large-scale IUU fishing, CCAMLR MCS measures tended to be based on conventional approaches (e.g., input and output controls) common to many fisheries enforcement agencies (Rayfuse 1998). These relied heavily on application of Flag State jurisdiction and fulfilment of Port State responsibilities. Table 4 shows that the bulk of CCAMLR MCS measures rely on prohibiting fishing

without due authorisation (CM 10-02), monitoring fishing location using vessel monitoring systems (VMS) (CM 10-04) and requiring notification of vessel movements. These were expanded to include at-sea (System of Inspection) and in-port inspections (CM 10-06 and 10-07) as well as comprehensive fisheries data reporting (Miller *et al.* 2004).

Expansion of Toothfish longline fisheries in the early to mid-1990s (fig. 4) moved CCAMLR to realise that traditional MCS alone is unlikely to be effective in combating a persistent and expanding IUU fishery (Agnew 1999). As indicated, this was a problem compounded by both CCAMLR area's size and the mix of jurisdictional conditions therein. The latter includes Coastal State jurisdiction, Flag State jurisdiction, and Non-Contracting Party involvement, as well as high seas rights under the LOS Convention (Molenaar 2001).

IUU fishing not only undermines CCAMLR CM, it also violates principles set out in other international fisheries agreements, such as UNFSA Article 18 on Flag State duties, as well as the obligations of Non-Members, or Non-Participants, in regional fisheries arrangements (UNFSA Article 17) and generally (LOS Convention Articles 116–119).

Being economically valuable and in some demand, Toothfish has attracted significant prices internationally over the past decade. As fishable stocks are located within and outside the CCAMLR Area, IUU fish caught in the CCAMLR waters have been difficult to track through the global trade cycle. IUU operators have benefited by being able to trade fish free from any attached regulatory restrictions and in relative obscurity with the origin of catches being hard to determine (Agnew 1999, Green & Agnew 2002, Sabourenkov & Miller 2004). Therefore, CCAMLR began developing measures in 1998 to improve monitoring of Toothfish landings, the subsequent access of associated products to international markets for fish caught by its members and by voluntary participating parties, in the Convention Area as well as in waters under the coastal state jurisdiction of members. This initiative culminated in the Toothfish Catch Documentation Scheme (CDS) entering into force on 7 May 2000.

Development of the CDS has been comprehensively documented elsewhere (e.g., Agnew 1999) and its provisions are clearly detailed in CM 10-05 (table 4). However, in addressing a number of key, and in many cases relatively novel, principles, the CDS strives to track global Toothfish trade and to restrict the access of IUU-caught Toothfish to international markets. It also enables CCAMLR to identify the origin of Toothfish entering the markets of all CDS Parties and to better determine if Toothfish are caught in the Convention Area consistent with CCAMLR CM. The most pervasive feature of the CDS is that it allows total Toothfish removals to be estimated, an essential prerequisite for stock assessment purposes. As updated from table 5 in Miller *et al.* 2004, the key underlying principles of the CDS:

- address CCAMLR Contracting and Non-Contracting Party fishing alike
- promote non-discriminatory, fair and transparent practices
- are practical and rapidly implementable
- apply to fishing both inside and outside the CCAMLR Area (i.e., recognise the "transboundary" nature of Toothfish distribution)
- encourage CCAMLR Non-Contracting Party participation
- include validation and verification procedures to raise confidence in the information produced
- outline the obligations of all participants
- prohibit entry of *Dissostichus* spp. into world markets in the absence of verified catch documents
- determine if *Dissostichus* spp. harvesting in the CCAMLR Area is consistent with CCAMLR CM;
- require Flag State authorisation for *Dissostichus* spp. harvesting both inside and Outside the CCAMLR Area
- set conditions for the sale of *Dissostichus* spp. seized or confiscated through enforcement action
- promote Flag State, Port State and importing State co-operation
- facilitate estimation of total *Dissostichus* spp. removals for global catch and stock assessment purposes.

Despite the fact that it complements similar global initiatives, Miller *et al.* (2004) have stressed that the CDS was never intended as a stand-alone measure, but rather as an integral component in a suite of CCAMLR measures to combat IUU fishing. Undoubtedly, however, it is still a major CCAMLR achievement in countering such fishing. Not only are evaluations of its effectiveness encouraging (Sabourenkov & Miller 2004, Willock & Lack 2006), the CDS is unique in scope and application and became fully operational within a relatively short period (less than two years). Its overall coverage now extends to more than 90% of the global Toothfish trade (Miller *et al.* 2004).

Using the CDS, participating parties have been able to deny Toothfish landings and/or shipments in the absence of attached documents. Such absence constitutes a rebuttable presumption aimed at triggering enforcement action. The CDS has also improved estimates of global Toothfish catch levels while highlighting incidents where malpractice and fraudulent documentation are occurring. Such qualities were instrumental in setting up two of the largest and most successful prosecutions under the Lacey Act for infringement of CCAMLR CM arising from illegal Toothfish trade into the United States (Oritz 2005, Anon 2006a). Together with evidence that the CDS's introduction has made trading in IUU-caught fish less profitable, it also appears to be having the desired effect of restricting market access to IUU-caught product (Green & Agnew 2002).

With the various improvements that have been drafted into CM 10-05 since it was first adopted, the CDS has also allowed CCAMLR to promote a multi-lateral and global approach to combat Toothfish IUU fishing. This has largely been possible since the CDS is globally applicable, while application of other CCAMLR CM is essentially limited to within the CCAMLR Area and to Contracting Parties alone. Furthermore, the CDS' implementation is entirely consistent with the provisions of UNFSA Articles 7, 8 and 17 as these relate to compatibility of measures, cooperation and Non-Contracting Parties.

Since it strives to minimise discrimination against any particular State, there is little doubt that the CDS' efficacy benefits from both enhanced international cooperation and also from a semblance of coherence with World Trade Organization requirements (Larson 2000). Further support for this view is evidenced by the clear aim of broadening the CDS' application globally through closer cooperation between CCAMLR and Parties to the Convention on International Trade in Endangered Species (CITES) via improved cooperation and information exchange between the two organisations (CCAMLR 2002 paragraphs 10.72–10.75).

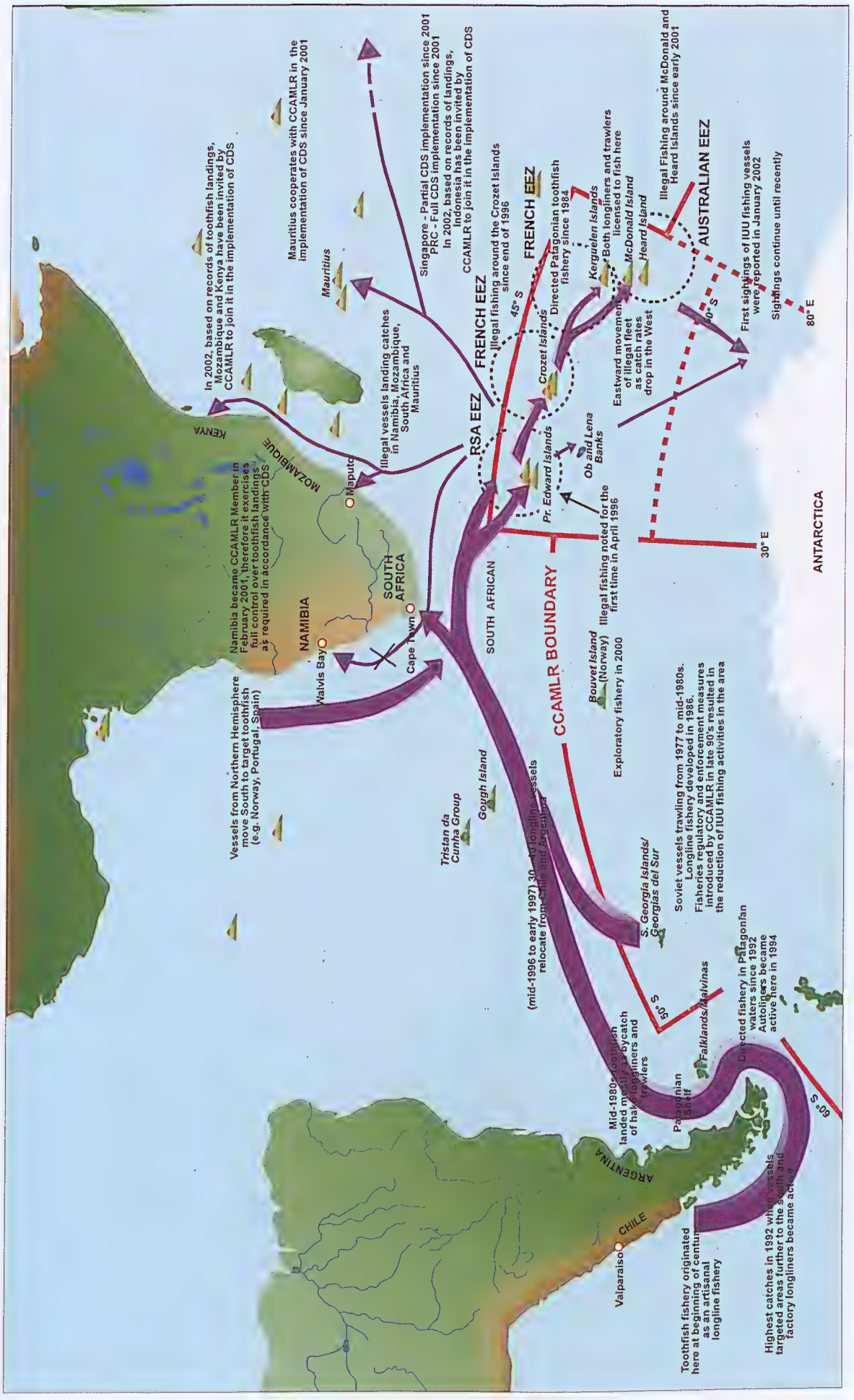
In 2002, based on records of toothfish landings, Mozambique and Kenya have been invited by CCAMLR to join it in the implementation of CDS
Mauritius cooperates with CCAMLR in the implementation of CDS since January 2001
Singapore - Partial CDS implementation since 2001
PRC - Full CDS implementation since 2001
In 2002, based on records of landings, Indonesia has been invited by CCAMLR to join it in the implementation of CDS
Illegal vessels landing catches in Namibia, Mozambique, South Africa and Mauritius
Illegal fishing around the Crozet Islands since end of 1996
Directed Patagonian toothfish fishery since 1984
Both longliners and trawlers licensed to fish here
Eastward movement of illegal fleet as catch rates drop in the West
Illegal Fishing around McDonald and Heard Islands since early 2001
First sightings of IUU fishing vessels were reported in January 2002
Sightings continue until recently
Illegal fishing noted for the first time in April 1996
Namibia became CCAMLR Member in February 2001, therefore it exercises full control over toothfish landings as required in accordance with CDS
Vessels from Northern Hemisphere move South to target toothfish (e.g. Norway, Portugal, Spain)
(mid-1996 to early 1997) 30 – 40 longliners vessels relocate from Chile and Argentina
Exploratory fishery in 2000
Soviet vessels trawling from 1977 to mid-1980s.
Longline fishery developed in 1986.
Fisheries regulatory and enforcement measures introduced by CCAMLR in late 90's resulted in the reduction of IUU fishing activities in the area
Mid-1980s toothfish landed mostly as bycatch of hake longliners and trawlers
Directed fishery in Patagonian waters since 1992
Autoliners became active here in 1994
Toothfish fishery originated here at beginning of century as an artisanal longline fishery
Highest catches in 1992 when vessels targeted areas further to the south and factory longliners became active
KENYA
MOZAMBIQUE
NAMIBIA
SOUTH AFRICA
Maputo
Walvis Bay
Cape Town
Mauritius
RSA EEZ
FRENCH EEZ
FRENCH EEZ
AUSTRALIAN EEZ
SOUTH AFRICAN
CCAMLR BOUNDARY
Crozet Islands
Pr. Edward Islands
Ob and Lena Banks
Kerguelen Islands
McDonald Island
Heard Island
Bouvet Island (Norway)
Gough Island
Tristan da Cunha Group
S. Georgia Islands/ Georgias del Sur
Falklands/Malvinas
Patagonian Shelf
ARGENTINA
CHILE
Valparaiso
45° S
60° S
40° S
30° E
80° E
ANTARCTICA

FIG. 4 — Development of IUU fishing in the CCAMLR Area (updated from fig. 4 in Miller et al. *2004).*

Despite the CDS' obvious benefits, the CM illustrated in table 4 clearly show that the former does not stand alone in combating IUU fishing. As a "package", combined with effective Coastal State action (e.g., see table 10 in Miller *et al.* 2004), application of the CDS, in combination with more traditional MCS measures, has provided positive indications of effective IUU deterrence. This conclusion is supported by a discernible decline in estimates of *Dissostichus* spp. IUU catch levels for recent years (fig. 5). Although such a decline could reflect diminishing Toothfish stocks, Baird (2006) remains optimistic that CCAMLR's enforcement efforts to counter IUU fishing have been positive when combined with vigorous Coastal State action, particularly in the sub-Antarctic Indian Ocean.

Finally, there is little doubt that the CDS provides the additional dimension of dealing with third-party involvement, where such a party is a State that is neither a Flag State fishing in the CCAMLR Area nor a CCAMLR Contracting Party. Consequently, Flag State enforcement is augmented. It has also extended responsibilities similar to those of CCAMLR Contracting Parties to other States participating in the Scheme (Miller *et al.* 2004). The latter is particularly important as it distinguishes between various IUU "actors" in terms of identifying flag, port, export and import State responsibilities. Such information is likely to be helpful in identifying those actually benefiting from IUU activities through facilitating identification of Toothfish end-users and trade locations (Vidas 2004).

Seabird incidental mortality

The 1999 FAO International Plan of Action for Reduction of Incidental Catch of Seabirds in Longline Fisheries (IPOA-Seabirds) (FAO 1999) indicates concern at (i) the negative consequences of such mortality on threatened seabird stocks, and (ii) possible impact(s) on fishing productivity and profitability.

The need to address incidental mortality of Antarctic marine living resources arising from harvesting activities is clearly alluded to in Article II.(3).(c) of the CAMLR Convention in terms of minimising the risk of irreversible ecosystem changes. By 1984, CCAMLR had requested members record the number, species and, where appropriate, age, size, sex and reproductive status of any birds or marine mammals taken incidentally during fishing operations (CCAMLR 1986 paragraph 42).

Initially CCAMLR estimated the number of albatrosses (mostly sub-Antarctic species) being killed annually at 45 000 in tuna longline (i.e., pelagic) fisheries outside the Convention Area (Croxall 1990). Although this was thought to be a conservative estimate, it was sufficiently high to substantiate claims that the serious declines observed in Albatross populations breeding in the CCAMLR Area could be attributed to such fishing activity (SC-CAMLR 1989, paragraph 6.7, SC-CAMLR 1990, paragraph 7.3).

With the introduction of demersal longlining for Toothfish around South Georgia in 1989, CCAMLR voiced its concern based on experiences with longlining elsewhere (CCAMLR 1989, paragraph 24). These focused on the potentially high levels of seabird mortality associated with longline fishing that arise when birds are hooked and drowned while feeding on baited hooks during line setting (particularly in daylight hours). At South Georgia, the risks were compounded by the relative proximity of fishing grounds to land-based breeding sites of threatened seabird species, predominantly albatrosses and petrels, at crucial times (SC-CAMLR 1989, paragraph 6.7, SC-CAMLR 1990, paragraph 7.3; Kock 2001).

Noting Australia and Japan's successes in reducing seabird bycatch in tuna longline fisheries (CCAMLR 1990, paragraph 5.3), CCAMLR initially mandated deployment of "tori poles" or "scare" lines to deter birds from taking

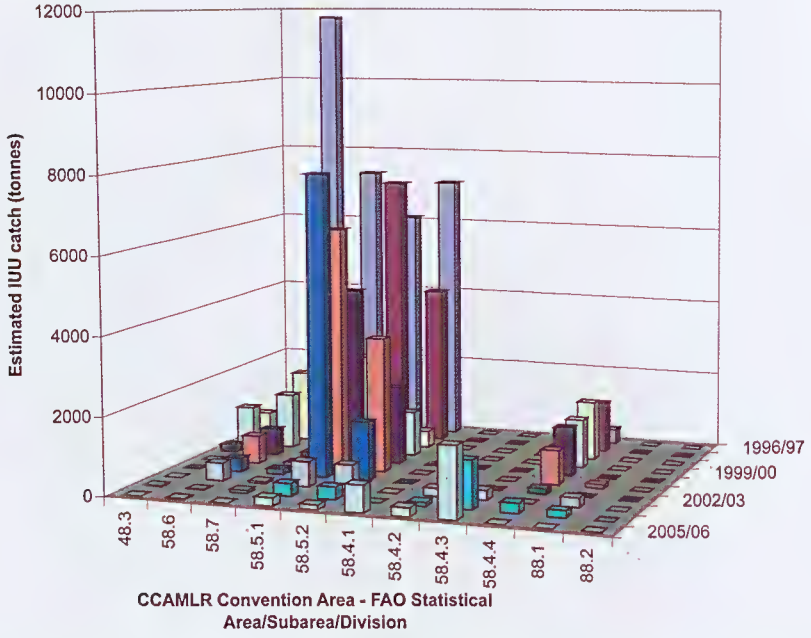

FIG. 5 — IUU catch estimates for the CCAMLR Area by statistical Subarea/Division for seasons 1996/97 to 2005/06 (updated from fig. 3 in Sabourenkov & Miller 2004).

baited hooks close to the surface, particularly during daytime line-setting. Combined with night-setting, these simple measures significantly reduce seabird catch and formed a basis for future CCAMLR seabird mitigation measures (see below). Attached economic benefits included reduction of bait loss and a consequent improvement in fishing efficiency (SC-CAMLR 1990, paragraph 7.5).

CCAMLR therefore became the first international organisation to institute comprehensive incidental seabird mortality mitigation measures. In 1989, the adoption of Resolution 5/VIII (CCAMLR 1989, paragraphs 107 and 108) aimed to minimise incidental seabird mortality. This was followed by CM 29/X the next year, which with substantial revisions (see table 4 in Miller *et al.* 2004) has endured as CM 25-02 (CCAMLR 1997–2006). CCAMLR, in the form of *ad hoc* WG-IMAF, continues to estimate potential seabird by-catch in proposed new and exploratory fisheries as well as monitoring by-catch of both seabirds and mammals in trawl fisheries (e.g., CCAMLR 2002, paragraph 6.22). A decade after CCAMLR's initial efforts to countenance mitigation of seabird incidental mortality, the bulk of its experiences were incorporated into the IPOA-Seabirds mentioned above.

Over the past seven years, seabird bycatch in CCAMLR-regulated longline fisheries has been reduced to almost insignificant levels. Since 1997 such levels have been negligible in Subarea 48.3, low in the South African EEZ in Subareas 58.6 and 58.7 and non-existent in Subareas 88.1 and 88.2. In 2006, seabird bycatch levels (fig. 6) in the CCAMLR Area were the lowest on record and for the first time an Albatross catch of zero was reported for the regulated longline fishery (CCAMLR 2006, paragraph 5.6). This success is largely attributed to compliance with CCAMLR by-catch measures and to delaying commencement of fishing until the end of the breeding season for most albatross and petrel species (Kock 2001).

Nevertheless, CCAMLR remains concerned that IUU fishing in the CCAMLR Area, combined with seabird by-catch in fisheries to the north, is still the major threat to many seabird populations in the Southern Ocean (e.g., CCAMLR 2002, paragraph 6.8). Estimates of potential by-catch levels associated with IUU fishing in each of the past nine years are also shown in figure 6. Since many albatrosses, Giant Petrels and White-Chinned Petrels breeding in the CCAMLR Area are declining at rates where extinction is a possibility, CCAMLR continues to view this as a compelling incentive for strict measures to combat IUU fishing (Kock 2001).

The observed decline in the estimated take of birds by the IUU fishery since the 2002/03 season, however, is difficult to explain. In the absence of clear information on the extent of mitigation being practised by that fishery, it is only possible to conclude that interactions between birds and the fishery have declined. This could be attributed to the IUU fishery having moved its location to areas more remote from bird feeding grounds; an explanation enhanced by recent trends in the IUU fishery, particularly in the Indian Ocean, over the past year or so (see figs 4, 5).

While no single mitigating measure is likely to eliminate *all* seabird mortality during longlining, CCAMLR's experience has indicated that it is crucial that lines be set to minimise visual detection, and feeding, by foraging birds on bait close to the surface. In CCAMLR's case this has been achieved by fishers complying fully with straightforward measures; namely regulation of offal discharge, streamer line deployment and night-setting. Nevertheless, refining, and enhancing compliance with, specified line-weighting regimes (especially for the Spanish longline system) remains a priority (CCAMLR 2002, paragraph 6.11.(i)). Line-weighting requirements for the Norwegian Autoline system were incorporated into CM 25-02 in 2003 (table 4).

CCAMLR also continues to encourage development of appropriate line-weighting requirements (CCAMLR 2002, paragraph 6.16.(iii)), while striving to improve seabird bycatch mitigation in the CCAMLR Area. In addition, it has drawn members' attention to potential modifications to provide facilities for underwater line-setting on new, or replacement, vessels (paragraph 7.197 in Annex 5 of SC-CAMLR 2000). Finally, CCAMLR continues to receive advice from the Scientific Committee, based on *ad hoc*

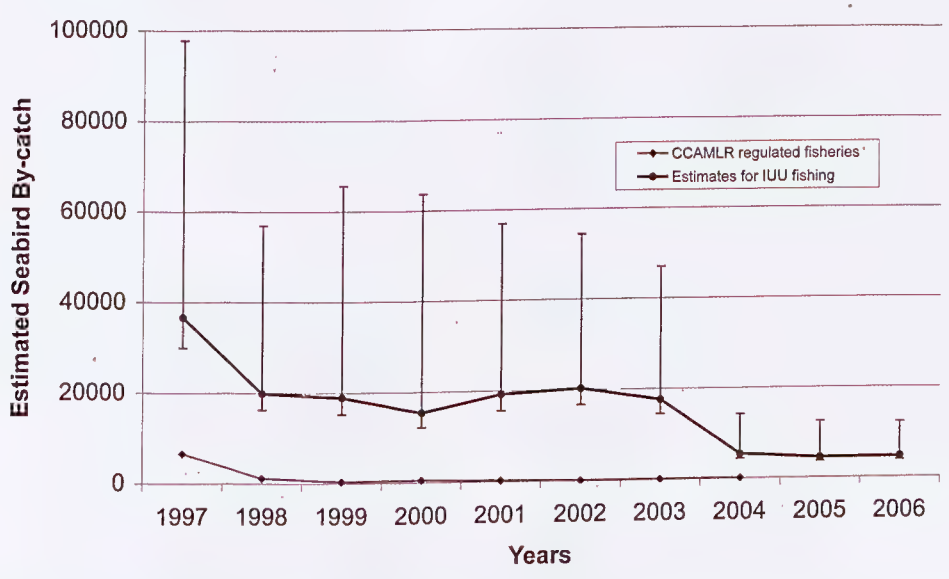

FIG. 6 — Estimated seabird bycatch in CCAMLR regulated and unregulated (IUU) longline fisheries in the CCAMLR Area (updated from fig. 3 in Miller et al. *2004).*

WG-IMAF's annual reviews of seabird bycatch mitigation measures. It also strives to keep abreast of international best practice while actively promoting cooperation with other management organisations (e.g., as per Resolution 22/XXV – CCAMLR 1997-2006).

Precautionary management of fisheries

Ideally, commercial fisheries development should not outstrip the information necessary to manage the sustainable, and scientifically defensible, exploitation of the stocks being targeted (Butterworth 1999). This allows for comparisons to be made of stock status before and after exploitation begins, with management action modified to maintain a target stock level. However, new fisheries are often exploited – even over-exploited – well in advance of essential management information becoming available, or even being collected. In this context, the precautionary elements of Article II of the CAMLR Convention "strive to minimise the risk of irreversible change(s) induced by effects of harvesting on target, and dependent, stocks".

On advice from its Working Group for the Development of Approaches to Conservation of Antarctic Marine Living Resources (WG-DAC) in 1989 (CCAMLR 1989, Annex. E), and from the Scientific Committee a year later (SC-CAMLR 1990, paragraph 8.7), CCAMLR sought to address management of new fisheries in the CCAMLR Area. For definitional purposes, a "new" fishery was considered to be a fishery on a species using a particular fishing method in a Statistical Subarea for which: (i) information on distribution, stock abundance, demography, potential yield and identity from comprehensive research/surveys or exploratory fishing have not been submitted to CCAMLR; or (ii) catch and effort data have never been submitted to CCAMLR; or (iii) catch and effort data from the two most recent seasons in which fishing occurred have not been submitted to CCAMLR (CCAMLR 1997–2006).

It was recognised that development of new fisheries "should be directly linked with elaborating scientific advice and management measures" to ensure that CCAMLR does not compromise its efforts to meet the objectives of Convention Article II (CCAMLR 1990, paragraph 9.3).

CCAMLR also accepted the Scientific Committee's advice (SC-CAMLR 1990, paragraph 289 in Annex 5) that certain vital information is essential for assessing the potential yield of a new fishery and that such information should be considered before full commercial development of a fishery begins so that any development may be kept consistent with Article II objectives (CCAMLR 1990, paragraph 9.4). This advice required prior notification of new fisheries as a basis for developing management measures consistent with conditions set out in both Articles II and IX of the CAMLR Convention (CCAMLR 1990, paragraph 9.5).

The considerations outlined in the previous paragraph led to adoption of CM 31/X in 1991 (CCAMLR 1991, paragraph 10.3). The key features of this measure were the need for prior notification of any new fishery and the fulfilment of attached conditions for its implementation. In its current form, CM 31/X now stands as CM 21-01 (CCAMLR 1997-2006), which expressly recognises that fisheries should be managed from the time that they are initiated. It also mandates pre-notification of the intent to commence a new fishery as well as sets conditions for collecting information on target and dependent species, and for limiting initial fishing catch and/or effort.

In 1993, CCAMLR concluded that following a year of fishing a new fishery becomes an "exploratory" fishery. CM 65/XII (now CM 21-02) was thus adopted in the same year to address fisheries that are no longer new, but for which critical management information remains unavailable (CCAMLR 1993, paragraph 8.39 and updated table 2 in Miller *et al.* 2004) to:

- Evaluate distribution, abundance, and demography of the target species, leading to an estimate of the fishery's potential yield
- Review the fishery's potential impacts on dependent and related species
- Allow the Scientific Committee to formulate and provide advice to CCAMLR on appropriate harvest catch levels, as well as effort levels and fishing gear, where appropriate.

Under CM 21-02, an "exploratory" fishery is one previously defined as "new" under CM 21-01. It continues to be defined as "exploratory" until the key conditions outlined above have been met (CCAMLR 1997–2006). Both "new" and "exploratory" fisheries are subject to rigid notification and review procedures before CCAMLR authorises fishing subject to a full assessment of stock yield having been undertaken. All other fisheries are therefore considered either to be "closed" (i.e., not specifically open to fishing as new or exploratory fisheries, or as closed by specific CCAMLR CM), or are classed as no longer being exploratory (i.e., since essential management and catch/effort information have become available).

The CCAMLR approach enshrined in CM 21-02 allows precaution to be continuously applied to exploratory fisheries and provides for collection of essential data to underpin full assessment of the fishery and stock(s) concerned. It also attempts to reduce the potential for irreversible change(s) to the ecosystem in which the fishery takes place.

A key attachment to CM 21-02 outlines a Data Collection Plan. Along with similarly attached Research and Fishery Operational Plans, this allows the Scientific Committee to undertake an annual review of developments to form the basis for its advice on prosecution of the fishery in question.

Since the late 1990s, numerous notifications for new and exploratory (especially exploratory) *Dissostichus* spp. fisheries in the CCAMLR Area have been received but not activated (see fig. 2 in Miller *et al.* 2004). This situation initially concerned CCAMLR (CCAMLR 2004, paragraphs 9.4–9.6), but has been ameliorated over the past two years by introduction of a recoverable fee for activated notifications introduced in 2005 (CCAMLR 2005, paragraph 3.12).

Additional to area-based regulatory measures setting catch limits and other restrictions (e.g., fishing season and effort limitations) for notified fisheries, CCAMLR has developed a single general measure (CM 41-01) to regulate exploratory *Dissostichus* spp. harvesting. CM 41-01 therefore contains some important elements to outline, *inter alia*, procedures to spread fishing effort, both temporally and spatially, data reporting requirements, bycatch limits for non-target fish species and mandatory deployment of CCAMLR International Scientific Observers designated in accordance with the Scheme of International Scientific Observation set up under Article XXIV of the Convention (CCAMLR 1997–2006). It also outlines provisions for seabird incidental mortality mitigation, bycatch regulation, environmental protection and data reporting.

CM 41-01 has undergone a number of significant modifications The most notable of these are summarised in table 3 of Miller *et al.* (2004). The introduction of small-scale research units (SSRU) in 2000 required that Toothfish exploratory fisheries operators collect data in a more scientifically rigorous way and that catch and effort be spread over a number of fine-scale areas (see fig. 1 in the 2006 version of CCAMLR 1997–2006). The SSRU approach is aimed at improving data collection on *Dissostichus* spp. distribution and abundance from areas where information is limited or absent. It also aims to minimise the risk of unacceptable and irreversible damage being inflicted on targeted stocks, as well as associated (i.e., bycatch) species, in a manner that allows insight into the key ecological processes likely to be involved.

The SSRU approach has been expanded to provide for additional gathering of scientifically-based information in the form of a tagging program for *Dissostichus* spp. (Annex 41-01/C of CM 41-01 – table 4) (CCAMLR 1997–2006). Such information is to be used in developing knowledge on stock dynamics and distribution in circumstances where such knowledge is generally lacking.

Following introduction of the above regime, CCAMLR then attempted to improve definition of when fisheries are no longer exploratory (i.e., when data for management purposes are sufficient to allow a fully regulated fishery). The subsequent debate focused on the need to review relationships between various stages of fisheries development to ensure, in the management context, a coherent progression from exploitation of an unexploited resource through various developmental phases to full commercial harvesting (CCAMLR 1997, paragraph 10.4). After several iterations, a Unified Regulatory Framework (URF) for CCAMLR fisheries was produced (SC-CAMLR 2000, paragraphs 7.2–7.20). In complementing existing regulatory requirements of relevant CM, the URF not only mandates prior notification of intended fishing, but also the establishment of Research and Fishery Operational and Data Collection Plans.

Another key URF element requires preparation of a basic reference document ("Fishery Plan") to be maintained by the CCAMLR Secretariat for each fishery in the CCAMLR Area. The Fishery Plan summarises information on the fishery concerned and includes a list of all attached regulatory requirements. Plans enable the Scientific Committee to develop advice on whether assessment of a particular fishery is required and/or possible. It also allows CCAMLR to formulate CM based on the total available information for the fishery concerned. To date, Fishery Plans have been developed for Krill, *C. gunnari* and Toothfish in Area 48 (South-West Atlantic).

As a general and precautionary principle, CCAMLR has agreed that until new information is received, no further advice on notified, but un-prosecuted fisheries should be developed (CCAMLR 2001, paragraph 10.3). Furthermore, measures such as CM 32-09 (table 4) clearly establish the principle that areas remain closed to fishing in the absence of specific measures to regulate harvesting.

Environmental protection

The provisions of sub-paragraphs 3.(b) and 3.(c) of CAMLR Convention Article II identify relatively broad objectives for ecosystem and precautionary management in the CCAMLR Area (Miller 2000, 2002). In this context, CCAMLR's approach over the past two decades has been comprehensively summarised by, amongst others, Constable (2002), Constable *et al.* (2000), Everson (2002) and Miller (2002). However, and as emphasised by Miller *et al.* (2004), a key point to note is that this approach has been guided by an operationally effective interpretation of Article II to account for pre-agreed key, and coherent, principles. As updated from tables 7 and 8 in Miller *et al.* (2004), these may be divided into underlying principles and an attached operational *pro forma*. The former comprises recognition that:

- Conservation includes rational use. The latter is subject to different interpretations, *inter alia,*
  (a) harvesting of resources is on a sustainable basis
  (b) such harvesting is conducted to ensure that the highest possible long-term yield can be taken from a resource, subject to the general principles of conservation in Article II of the Convention being met
  (c) the cost-efficiency of harvesting and management should be given due weight.
- Harvesting and/or associated activities should be conducted according to accepted conservation principles.
- As a general principle, the ecosystem(s) should be maintained in a state where:
  (a) present and future options are preserved, which requires preventing decreases in harvested population size to levels below which stable recruitment and the maintenance of ecological relationships between harvested, dependent and related populations are ensured
  (b) risk(s) of irreversible change or long-term adverse effects of harvesting and/or associated activities should be minimised
  (c) wherever applicable, both consumptive and non-consumptive resource use should be given due weight and should be maximised on a continuing basis.
- Management decisions should account for uncertainty associated with imperfect knowledge and should be "precautionary" (i.e., conservative) in the absence of complete knowledge.
- Measures conserving resources should be formulated and applied to avoid wasteful use of other resources.
- Planned and actual resource use should be preceded, and accompanied, by surveys to assess resource potential, the monitoring of resource status and associated analysis of ancillary data.

The CCAMLR operational *pro forma* outlined has applied four key actions to achieve these principles:

- development of operational objectives to articulate target status for relevant ecosystem aspects
- development of methods to assess ecosystem status
- elaboration of decision rules for adjusting harvest controls to account for differences between assessments and agreed objectives
- development of methods to address uncertainty [including ecosystem functional ("Physical World") uncertainty] to facilitate the reaching of scientific consensus.

At the risk of some repetition, this section will focus on the efforts of CCAMLR to minimise harvesting effects on the sub-Antarctic environment and to better understand the environment in which the marine living resources for which it is responsible are found.

Table 5 shows that CCAMLR has adopted various measures to manage fishing and other CCAMLR-related activities to account for general environmental and, by implication, ecosystem "concerns". Such measures are consistent with the requirements of other international

instruments such as the 1991 *Madrid Protocol to the Antarctic Treaty on Environmental Protection* and the 1973/78 *International Convention for the Prevention of Pollution from Ships* (*MARPOL* 73/78), especially its Annex. 5. They also conform with general provisions outlined in Article IX.(3). (b) and (c) of the CAMLR Convention.

In 2006, CCAMLR amalgamated most of the environmental provisions from a number of CM into a single measure, CM 26-01 (table 5) (CCAMLR 1997–2006). This not only served to streamline reference to such measures, but also provided a more unified approach to addressing the environmental effects of harvesting activities that CCAMLR is trying to avoid. CM-26-01 thus regulates garbage disposal and attempts to minimise marine pollution by fishing vessels through dealing with disposal of plastic materials (CM 26-01 paragraphs 1 to 4) and prohibiting offal dumping as well as the discharge of a number of potential marine pollutants (e.g., fuel oil and sewage) in high latitude areas south of 60°S (paragraph 5 in CM-26-01). CM 26-01 also prohibits translocation of live poultry and mandates removal of non-consumed poultry products south of 60°S(paragraph 6 in CM 26-01). It is not hard to envisage such regulations being extended throughout the CCAMLR Area especially CM 26-10 paragraph 6. This particular provision could prove an important prerequisite for minimising risk of avian influenza spreading into the CCAMLR Area.

Probably more relevant to the sub-Antarctic, CCAMLR has recently adopted two measures directly aimed at limiting the impact of environmental damage arising from potentially unsuitable fishing practices. In keeping with growing international concerns about such practices (United Nations 2006, paragraphs 58–60), CM 22-04 and 22-05 provide for an interim-prohibition on deep-sea gillnetting and restriction on bottom-trawling in the high seas respectively.

Table 5 also shows that various other CM close particular areas to fishing generally (CM 32-02, 32-03 and 32-09) or limit fishing to specific seasons (CM 41-02-41-11, 42-01/o2, 43.2 to 43-04, 51-01 to 51-03 and 61-01). Combined with prohibition of directed fishing on certain species (CM 32-04 to 32-17) or general invocations aimed at conserving selected species (e.g., sharks – CM 32-18), such measures have a positive environmental effect as they not only strive to protect fished or related species at key times, they also afford general protection to the marine environment (e.g., CM 32-02 and 32-03) since any potential environmental consequences of harvesting are minimised. Coupled with bycatch regulation (CM 25-02/03, 33-02/03, 42-01/42.02, 43-02 to 43-04 and 52-01), CCAMLR species protection measures strive to mitigate indirect harvesting effects.

An additional suite of CM deals with the way that different kinds of fishing gear are to be used in the Convention Area. These require that gear be marked for identification purposes (CM 10-01) and set out conditions for gear construction (CM 25-02 and 25-03) and testing (CM 24.02 and 24-03). As such, mesh size regulations (CM 22-01 to 22-03) not only set net construction standards, they also serve to protect parts of any targeted stocks as a function of body size.

Therefore, and from a general environmental awareness perspective, CCAMLR stands as one of the few, if not only, organisations of its kind to have attempted to address specifically fishing vessel safety standards. While the CM concerned outline operational safety requirements (e.g., minimum lighting standards during fishing – CM 25-02 and 25-03), they are also more general in nature. In this regard, Resolution 20/XXII is globally unique in linking the licensing of vessels fishing in high latitudes to a minimum ice classification requirement.

Finally, the CCAMLR Ecosystem Monitoring Programme (CEMP) was initiated in 1984 (Agnew 1997, Miller 2002) to improve CCAMLR's understanding of potential interactions between fishery, harvested species and the environment. CEMP's major purpose is to monitor key life-history parameters of selected dependent, or "indicator", species likely to be affected by the availability of harvested species. The monitoring sites are afforded special protection by various CM (CM 91-01 to 91-03).

Using CEMP information, CCAMLR is actively engaged in developing a management procedure to formally account for ecosystem considerations, and environmental influences, in its decision-making (Constable 2002). The procedure being followed is illustrated in figure 7 and it can be seen that it strives to give effect to the *pro forma* approach outlined above as it addresses the need (updated from Miller *et al.* 2004) to:

- apply correct and timely decisions to facilitate fulfilment of Article II conservation principles
- undertake monitoring of sufficient power so that harvest controls do not negatively affect dependent predators
- allow sufficient time to detect and rectify harvest-induced changes in the ecosystem within two or three decades as mandated by Article II
- refine assessments of harvested stock yield to account for new estimates of key demographic parameters and by dividing precautionary yield into small-scale management units (SSMU) of appropriate scale to improve predictive power and spread any risk of irreversible ecosystem changes
- develop operational objectives for non-harvested species to account for uncertainties associated with ecosystem function and dynamic relationships amongst predators, and particularly between predators and prey.

The management procedure itself comprises a set of rules to adjust harvest levels based on objective assessment so that the management objectives illustrated in figure 7 have a high probability of being fulfilled. The state of the ecosystem in question is observed through monitoring (i.e., via CEMP). Regular assessments are therefore undertaken to account for uncertainty associated with ecosystem functioning as well as potential relationships between monitoring and that ecosystem, including its physical environment. This particular initiative remains a key priority for CCAMLR in terms of fulfilling the requirements of Article II of the CAMLR Convention.

CONCLUSIONS

CCAMLR as an organisation has learnt much during its 25-year existence. To reflect on these lessons, Australia and Chile hosted a CCAMLR Symposium in April 2005 to provide a forum for frank and open discussion of CCAMLR's past, present and future (Anon. 2005). One of the symposium's key products was the following list of issues and ideas (based on information provided in paragraphs 16.6 to 16.18 of CCAMLR 2005 and Anon. 2005) for further consideration by the participants, CCAMLR, its Member States and others. The list was grouped into two main categories, with each category requiring specific topics to be addressed, objectives to be met or actions to be taken:

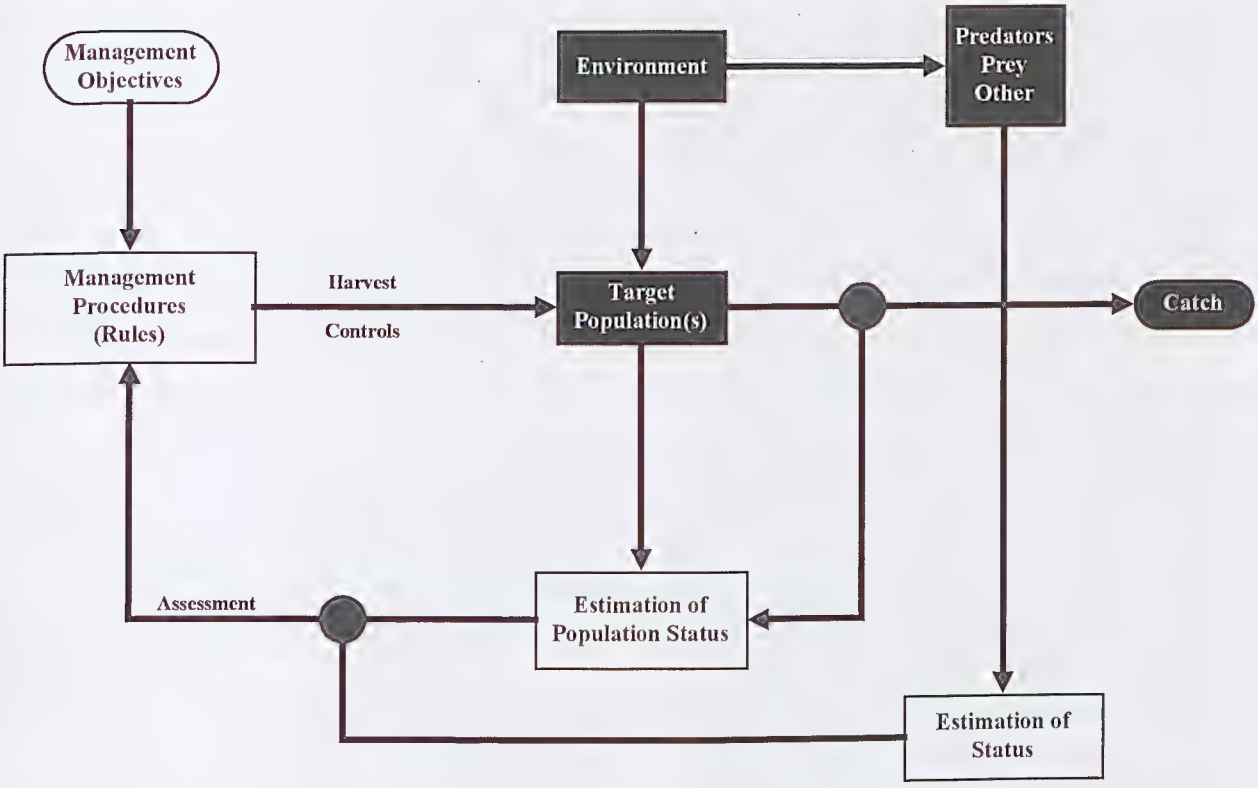

FIG. 7 — CCAMLR's ecosystem management approach to address the effects of harvesting on dependent and related species (see text for details) (adapted from Constable 2002 with permission).

- Threats to be faced
  - expectations and resources mismatched
  - conflicting objectives
  - legitimate stakeholder participation
  - uncertainty concerning key management factors or parameters
  - equity issues
  - lack of standardized ecological value system to benchmark management initiatives
  - insufficient human and/or logistic capacity (particularly for MCS).
- Topics for co-operation and/or action and co-ordination
  - sustainable marine living resources
  - environmentally "healthy" areas
  - effective institutions
  - common standards (e.g., for assessment or management action)
  - exchange of relevant information
  - robust legal provisions (especially for CM)
  - effective MCS (especially on-water enforcement)
  - objective and robust science.

The various topics were discussed in detail and were seen to warrant future priority action (CCAMLR 2005, paragraphs 16.10–16.18). A number of the items listed for future action, and in CCAMLR (2005, paragraphs 16.12 and 16.5), have since been addressed. Particular achievements include initiatives to address bioregionalisation of key species as a precursor to establishing objectively defined marine protected areas (MPAs) (paragraphs 6.1–6.6 in CCAMLR 2006) and CM 22-04 and 22-05 aimed at addressing the United Nations' call for action on destructive fishing practices. Further work has also been identified to use CEMP data in developing models for sub-dividing the Area 48 krill catch limit between SSMU (paragraph 4.9 in CCAMLR 2006) and to improve information flow between CCAMLR and other regional fisheries management organisations on matters of mutual concern (paragraphs 16.59–16.66 in CCAMLR 2006). These actions are not only precedent-setting in their own right, they indicate openness and transparency to support the notion that CCAMLR continually strives to improve its performance in the execution of its mandate. As already indicated (Small 2005), these are qualities that serve to demonstrate that CCAMLR leads other Regional Fishery Management Organisations ("RFMOs") in assessing its own performance through introspective, dynamic, flexible and reflective review. To this end CCAMLR has a standing item on its annual agenda to consider implementation of the Convention's objectives. This particular item spawned the CCAMLR Symposium outlined above.

CCAMLR has learnt a number of other key lessons over the past 20 years (1986–2006), namely:

- Good and tractable science is essential for addressing large management uncertainties.
- Proactive management and pre-agreed decision rules minimise potential conflict.
- Management action should be realistic, dynamic, flexible and monitorable.
- At-sea scientific observation is an extremely valuable source of essential fisheries information.
- Wide MCS is essential for effective compliance enforcement (especially in respect of IUU fishing).
- Formal processes to address new and exploratory (i.e., "developing") fisheries are essential for effective management and the accrual of necessary data.
- CCAMLR cannot solve all its problems alone (especially

in respect of any transboundary effects), so mandating good cooperation with RFMOs of similar interest or mandate.

- IUU fishing compromises everything by requiring a substantive commitment of valuable, and often limited, resources as a counter as well as by compounding uncertainty.

As indicated here and supported by Constable (2006), CCAMLR:

- Demonstrates the attributes of both an RFMO as well as wider conservation responsibilities (see also CCAMLR-XXI/BG/13 and CCAMLR 2002, paragraphs 15.1–15.2).
- Has instituted a precautionary approach to fisheries management.
- Stands alone internationally as the leading regional management organisation in terms of benchmarking best-practice for an ecosystem approach to managing fishing activities in waters outside national jurisdiction.

CCAMLR has not achieved the above alone, and it has continually strived to cooperate with neighbouring organisations on matters of common interest such as seabird incidental mortality (e.g., International Convention for the Conservation of Atlantic Tuna [ICCAT]) and transboundary management of Toothfish (Convention on the Conservation of Fisheries Resources in the South East Atlantic [SEAFO]). It also encourages Non-Contracting Parties to become involved in its work, such as through the CDS and Resolution 24/XXIV (table 4), to ensure that CCAMLR's conservation efforts benefit from full information input in determining the global extent of *Dissostichus* spp. harvesting.

This kind of cooperation indicates the far-sightedness of Articles X, XI and XXIII of the CAMLR Convention. It is perhaps fitting that 25 years after the Convention entered into force the intent of these particular articles remain relevant. Along with other CCAMLR Convention provisions, most notably Article II, the examples presented here reinforce CCAMLR's unique standing as a leader in ocean governance efforts globally.

Finally, it must be reiterated that IUU fishing stands as the most serious threat to the efforts of CCAMLR and other RFMO (Anon. 2006b) to manage the sustainability of the marine living resources for which they are responsible. Not only is CCAMLR hindered by the size and remoteness of the CCAMLR Area in addressing this threat, the involvement of Non-Contracting Parties and the need to deploy scarce resources to address IUU fishing in all its facets have compounded the challenge faced by the Commission and its members (Vidas 2004, Baird 2006). Consequently, the effective elimination of IUU fishing has come to rest on improving global cooperation as much as on any single measure or management strategy (COFI 2005). Nevertheless, as suggested by Willock & Lack (2006), and based on its past performance highlighted in this paper, CCAMLR remains the obvious leader to follow.

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APPENDIX 1
Acronyms referred to in this paper

ATS	Antarctic Treaty System
CAMLR Convention	Convention on the Conservation of Antarctic Marine Living Resources
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CDS	Catch Documentation Scheme
CEMP	CCAMLR Ecosystem Monitoring Programme
CITES	Convention on International Trade in Endangered Species
CM	Conservation Measure(s)
COFI	Committee for Fisheries
EEZ	Exclusive Economic Zone
FAO	Food and Agricultural Organisation of the United Nations
EAF	Ecosystem-Based Approach to Fisheries
HSTF	Inter-Ministerial Taskforce on IUU Fishing
IPOA	International Plan of Action
IUU	Illegal, Unreported and Unregulated
LOS Convention	1982 United Nations Convention on the Law of the Sea
MCS	Monitoring, Control and Surveillance
RFMO	Regional Fisheries Management Organisation
SCAF	Standing Committee on Administration and Finance
SCIC	Standing Committee for Implementation and Compliance
SSMU	Small-Scale Management Unit(s)
SSRU	Small-Scale Research Unit(s)
UNCED	1992 United Nations Conference on Environment and Development
UNFSA	1995 United Nations Fish Stocks Agreement
URF	Unified Regulatory Framework
WG-EMM	Working Group for Ecosystem Monitoring and Management
WG-FSA	Working Group for Fish Stock Assessment
WG-IMAF	Working Group on Incidental Mortality Associated with Fishing
WSSD	World Summit on Sustainable Development

INTERNATIONAL INSTRUMENTS AND ARRANGEMENTS IN THE SUB-ANTARCTIC

by Andrew Jackson

(with one text-figure and one table)

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This paper places the sub-Antarctic region in its international context by contrasting the sub-Antarctic's geographical qualities with the region's international legal and political characteristics. It shows that the international aspects of the legal regime applying in the sub-Antarctic are less developed than in the Antarctic. An overview is provided of some of the most relevant international instruments and arrangements that apply. This includes an analysis of some of the matters that are regulated and some that are not regulated. It is concluded that there is no requirement for a dedicated international regime in the sub-Antarctic, but there is substantial scope for further internationally cooperative arrangements to address the immediate issues facing the sub-Antarctic region.

Key Words: sub-Antarctic islands, international law, maritime law, environmental law, Antarctica, Southern Ocean.

INTRODUCTION

Is the sub-Antarctic special?

Most of the sub-Antarctic region is characterised by bleak expanses of ocean with few landfalls. The vast majority of the area embraced by the sub-Antarctic, where ocean encircles the globe, is essentially devoid of continental intrusions. The main exception is southern South America which, at its southernmost extremity, is in many ways sub-Antarctic with respect to climate, biogeography and the cultural aspects of small and remote communities.

It is therefore useful to look at whether the dominance of the ocean and the relative lack of inhabited land in the sub-Antarctic give rise to special international instruments and arrangements. From a legal and political perspective, the sub-Antarctic region is quite unlike the area south of 60°S. Most Antarctic policy advisers look beyond the sub-Antarctic to Antarctica, where there are more challenging jurisdictional issues and geopolitical forces calling for attention. The absence of universal recognition of territorial claims in that area underpinned the negotiation of the Antarctic Treaty (1961). The 1959 Treaty set aside sovereignty arguments and allowed international cooperation to proceed on a continental and, some would say, global scale. This was remarkable and also critical to providing the governance framework for essentially all human activities — a special solution for a special place.

The Treaty itself spawned what is now known as the Antarctic Treaty system, which has developed into a wide-ranging and largely integrated regime for regulating activities south of 60°S and, equally important, for providing forums for consultation between actors in the Antarctic. This has had the effect of diminishing the effect of other international instruments in the Antarctic. The Treaty "system" is usually described as embracing the numerous international agreements, instruments and institutional arrangements that flowed from the Treaty.

By contrast, north of 60°S, we have what is an equally special place — but we do not have an equally special solution to its governance needs. In the sub-Antarctic there is a much broader opportunity for a wide range of other international and domestic regimes to take full effect. A coherent single regime, as applies in the Antarctic, is not mirrored in the sub-Antarctic.

While different from the Antarctic, the sub-Antarctic region is also clearly different from the temperate areas further north. For a start, it is maritime, remote and barely inhabited (although it would be wrong to assume that any of it is uninhabitable). Sovereignty issues take a lower profile. The sub-Antarctic is, in terms of international law, not part of the Antarctic regime, or subject to an international regime of its own. This comes in part from its remoteness and, to a large degree, the absence of permanent human population. International instruments are, however, increasingly being applied in the region.

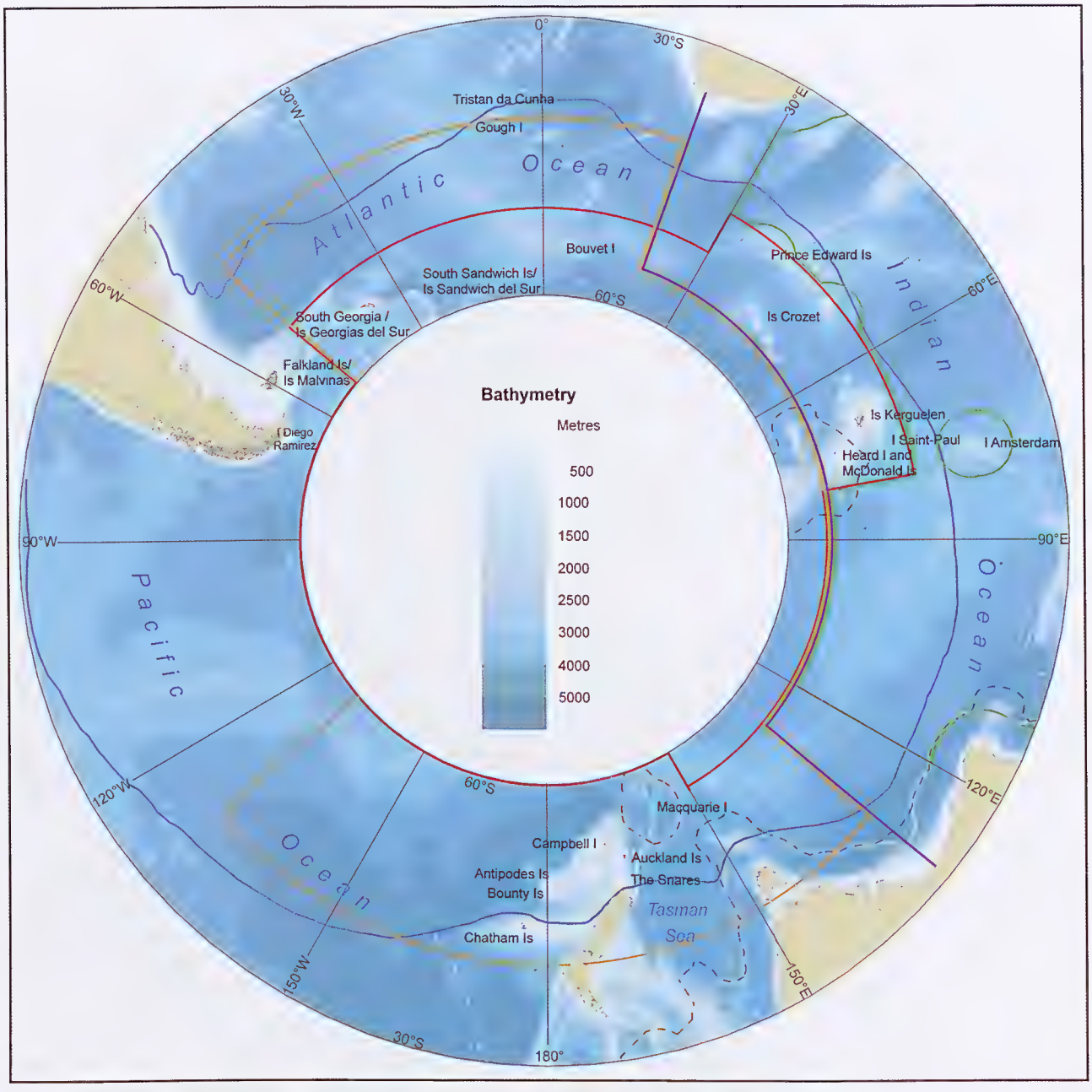
Unlike more temperate areas, the sub-Antarctic is generally not industrialised, although historically this was not the case. Past industrial occupation of several sub-Antarctic islands for sealing for skins and oil no longer applies. In some case the sites and relics associated with such use are recognised as having heritage values. Fishing is a current industrial use, and tourism is an intermittent commercial use of the region.

While much of the interest in the sub-Antarctic region focuses on the islands, most of the region is comprised of ocean. International maritime law therefore takes on particular importance, currently with particular respect to marine living resources, and other aspects of international law may have increasing application with respect to potential future interests.

International environmental instruments are especially relevant to the islands. The now well-recognised natural values of the sub-Antarctic have precipitated a growing interest in the application of international environmental management and protection regimes. That said, the sub-Antarctic has not had detailed assessment of the need for integration of the international regimes that apply.

So the sub-Antarctic is special in terms of the application of international instruments. Much of the uniqueness is explained by the remote maritime and island nature of the region and, arguably, there is potential for extending the application of international environmental and other instruments. There is also scope for harmonising the application of instruments in domestic law.

Other papers in this volume have sought to define the sub-Antarctic. For a definition of the sub-Antarctic useful to understanding the region's international arrangements, a map of the region would blank out the Antarctic Treaty area and the major inhabited land masses of Australia, New Zealand, South America and South Africa. The sub-Antarctic would be neatly cut off at 60°S. However, to the north there is no legal or geopolitical boundary and the sub-Antarctic map-maker might resort to an oceanic boundary such as the Subtropical Front which is the northernmost extent of sub-Antarctic waters (Orsi *et al.* 1995). However, to do this would exclude the Chatham Islands, Tristan da Cunha, Îles Amsterdam and Îles St Paul which lie just north of the Front. It is therefore expedient to draw the line at around 30° S. Using these boundaries the map becomes a sub-Antarctic "doughnut" comprised of a vast marine area with tiny flecks of land which are the sub-Antarctic islands (fig. 1).



Sub-Antarctic Region

Jurisdictional and Administrative Boundaries

Australian Government
Department of the Environment and Water Resources
Australian Antarctic Division

Polar Stereographic projection.
Produced by the Australian Antarctic Data Centre, Aug 2007
Map available at : *http://aadc-maps.aad.gov.au/aadc/mapcat/*
Map Catalogue No. 13415

- CCAMLR Area boundary
- Continental shelf limit of Australian territory
- Outer limit of Australian Exclusive Economic Zone
- Subtropical Front
- Southern Indian Ocean Fisheries Agreement boundary
- Southern Ocean Whale Sanctuary boundary
- Indian Ocean Whale Sanctuary boundary

FIG. 1 — Sub-Antarctic region: jurisdictional and administrative boundaries.

Table 1 indicates the countries which can be regarded as the sub-Antarctic states. These are the states exercising or asserting jurisdiction over lands in the sub-Antarctic region. These states are generally party to the international instruments and arrangements applying in the region.

MARITIME AND FISHERIES INSTRUMENTS THAT APPLY IN THE SUB-ANTARCTIC

Law of the Sea Convention

The Law of the Sea Convention (United Nations Convention on the Law of the Sea, 1982) seeks to provide governance of the world's oceans. It promotes peaceful use of the oceans and equitable use of resources. All of the sub-Antarctic states are party to UNCLOS.

Among other things, the Convention provides for the assertion of maritime zones subject to national jurisdiction. A line extending from the shores of a sub-Antarctic island into the great Southern Ocean would cross a number of UNCLOS zones.

TABLE 1
The sub-Antarctic states

State	Interest[1]
Argentina	Georgias del Sur Islas Malvinas Islas Sandwich del Sur (Southern Argentina and its islands also extend south of the Subtropical Front)
Australia	Heard Island and McDonald Islands Macquarie Island
Chile	Islas Diego Ramirez (Southern Chile and its islands also extend south of the Subtropical Front)
France[2]	Île Amsterdam Île Kerguelen Île Saint-Paul Îles Crozet
New Zealand	Antipodes Islands Auckland Island Balleny Islands Bounty Islands Campbell Island Chatham Islands The Snares
Norway[2]	Bouvetøya
South Africa	Marion Island Prince Edward Island
United Kingdom[2]	Falkland Islands Gough Island South Georgia South Sandwich Islands Tristan da Cunha

[1] This list is not intended to be exhaustive, nor is it intended to reflect on unresolved questions of sovereignty. It excludes islands within the Antarctic Treaty area.
[2] A Northern Hemisphere state.

It would first cross the Territorial Sea. The Territorial Sea is established by Article 2 of UNCLOS and gives the coastal state sovereignty to the waters, seabed and airspace — generally to 12 nautical miles. A Territorial Sea is asserted by all sub-Antarctic coastal states. At 24 nautical miles there is the limit of the Contiguous Zone (Article 33 of UNCLOS) within which a coastal state may prevent infringement of certain aspects of its domestic law.

The Exclusive Economic Zone (EEZ) is crossed next. The EEZ is established by Part V of UNCLOS. Among other things, the EEZ provides rights to the living and non-living resources of both the water column and the seabed. It generally applies to a limit of 200 nautical miles, but it is subject to delimitation with other coastal states (and there are several examples of delimitation agreements in the sub-Antarctic region — for example, the agreement between Australia and France with respect to the otherwise overlapping EEZs generated by Australia's Territory of Heard Island and McDonald Islands and the France's Îles Kerguelen). EEZs are asserted in the sub-Antarctic region by all of the coastal states in the sub-Antarctic.

Even further from the coast comes the area of extended continental shelf. This zone is established by UNCLOS Article 76 which, in essence, provides for exclusive access to the resources of the seabed (as opposed to the water above) in the area beyond the EEZ. This zone can only exist if a physical continental shelf can be shown to exist and to extend beyond the EEZ. This needs to be established by submitting data (such as bathymetric and seismic data), to the Commission on the Limits of the Continental Shelf which is established under UNCLOS to assess and provide recommendations on the shelf areas identified by coastal states.

While sub-Antarctic states have generally asserted territorial seas and EEZs, matters are still evolving with respect to the continental shelf beyond the EEZ. So far, submissions of data to define extended continental shelves in the sub-Antarctic region have been lodged by Australia (in November 2004) and New Zealand (in April 2006) — but recommendations on these submissions are yet to be made by the Commission on the Limits of the Continental Shelf. Whether or not extended shelf claims will be made in respect of other sub-Antarctic islands remains to be seen as the provisions of Article 76 are only just starting to be implemented by states parties to UNCLOS.

Beyond the extended continental shelf is the region described by UNLCOS as "the Area", which is subject to special rules that reflect the principle of the common heritage of mankind, and is controlled by the International Seabed Authority. The boundaries of the Area have not yet been defined, but the sub-Antarctic region consists of vast regions of the Area.

Both the extended continental shelf and the Area are issues which over the next few years may result in some new lines on the sub-Antarctic map.

It should also be noted that these maritime boundaries may change from time to time. In geological time scales, many sub-Antarctic islands are quite young and land-masses are continuing to emerge — in some cases quite rapidly where there is active volcanism. It is interesting to speculate on the new claims that might be asserted if new islands emerge, or indeed lands that might be lost if baselines retreat because of sea level rise — but these are matters for future generations.

CCAMLR

CCAMLR (Convention on the Conservation of Antarctic Marine Living Resources 1980) provides for the conservation of living marine resources of the Antarctic. Article II paragraph 2 of the Convention defines conservation as including rational use. The Convention's area of application roughly approximates to the area south of the Antarctic Polar Front and therefore much of it extends north of the Antarctic Treaty area, well into the sub-Antarctic. All of the sub-Antarctic states are party to CCAMLR.

Many sub-Antarctic islands are in the CCAMLR area — but not all. For example, in the immediate region of Australia, Macquarie Island and New Zealand's Auckland Island and Campbell Island are outside the CCAMLR area, albeit they support ecosystems and fisheries with many similarities to islands within the CCAMLR area

The CCAMLR regime includes the so-called "Chairman's Statement" (CCAMLR 1980, pp. 23–24) which essentially allows states whose island territories are within the CCAMLR area to exercise their domestic jurisdiction in accordance with CCAMLR Conservation Measures and to apply more stringent national measures in their waters if they wish. Furthermore, it allows for these coastal states to take enforcement action as a sovereign act and it allows a state to opt out of a Conservation Measure. This provision has been used from time to time in limited circumstances.

Other fisheries regimes

Other relevant fisheries regimes and agreements include the Whaling Convention (International Convention on the Regulation of Whaling 1946) which sets out to "provide for the proper conservation of whale stocks and thus make possible the orderly development of the whaling industry". There are well-known debates within the International Whaling Commission with respect to how the Commission goes about meeting the Convention's objectives and the various aspirations of the parties. The Whaling Convention is relevant as sanctuaries established under the convention embrace the waters south of 40°S. The Indian Ocean Sanctuary and the Southern Ocean Whale Sanctuary take in the waters of several sub-Antarctic islands.

CCSBT (the Convention for the Conservation of Southern Bluefin Tuna 1993) provides for the conservation and optimum use of this highly prized pelagic species. The sub-Antarctic states that are party to CCSBT are Australia and New Zealand. Other parties to the Convention are Japan, the Republic of Korea and the Fishing Entity of Taiwan and thus they have an interest in the sub-Antarctic region because the convention itself specifies no geographical limits, the range of the Southern Bluefin Tuna range extends into the region, and the fish are caught there.

The Australia/France maritime cooperation treaty (Treaty Between the Government of Australia and the Government of the French Republic on Cooperation in the Maritime Areas Adjacent to the French Southern and Antarctic Territories (TAAF), Heard Island and the McDonald Islands 2003) provides for cooperation in the maritime areas adjacent to France's Îles Kerguelen and Australia's Territory of Heard Island and McDonald Islands. The Treaty sets out to facilitate cooperation in responding to illegal, unregulated and unreported fishing.

The Southern Indian Ocean Fisheries Agreement (2006) is expected to enter into force in the near future. The agreement includes the waters around Île Amsterdam and Île Saint-Paul. The agreement provides for cooperation between states, organisations and fishing entities having an interest in the fishery resources of the Southern Indian Ocean to ensure compatible conservation and management measures.

INTERNATIONAL ENVIRONMENTAL INSTRUMENTS

Some environmental instruments apply, or are capable of applying, to some or all of the sub-Antarctic islands. Most of these instruments involve matters or actions that cross jurisdictional boundaries.

World Heritage Convention

The World Heritage Convention (Convention for the Protection of the World Cultural and Natural Heritage 1972) sets out to protect sites of outstanding and universal value. All states with sub-Antarctic islands are party to the Convention. The first listing of sub-Antarctic properties was in 1997 with the inscription of Australia's Macquarie Island (listed for its value in representing significant ongoing geological processes in the development of landforms and for its aesthetic values) and the Territory of Heard Island and McDonald islands (listed for geophysical values, as well as for the values in demonstrating ongoing ecological and biological processes). The New Zealand sub-Antarctic islands followed in 1998.

World Heritage nominations have been made for Marion Island and Prince Edward Island as a single site and it is expected that a decision will be made to inscribe the property on the World Heritage list. Nominations for other sub-Antarctic properties are not anticipated in the immediate future.

Bonn Convention

The Bonn Convention (Convention on Migratory Species 1979) aims to conserve terrestrial, marine and avian species throughout their range. All of the sub-Antarctic states are party to the Convention. The Convention is relevant to all the sub-Antarctic islands because of the number of migratory species involved, especially migratory birds that occur in the region.

ACAP

ACAP (Agreement on the Conservation of Albatrosses and Petrels 2001) was developed under the auspices of the Bonn Convention and entered into force in 2004. Its objective is to conserve albatrosses and petrels by coordinating activities to mitigate known threats. The parties to ACAP with sub-Antarctic interests include Argentina, Australia, Chile, France, New Zealand, Norway, South Africa and the United Kingdom. ACAP is relevant to all the sub-Antarctic islands because of the ubiquitous presence of these iconic bird species, many of which are threatened by fishing practices in the Southern Ocean.

Ramsar Convention

The Ramsar Convention (Convention on Wetlands of International Importance Especially as Waterfowl Habitat 1971) provides for the conservation and wise use of wetlands through national and regional actions and international cooperation. It has a special interest in waterbirds. All of the states with sub-Antarctic islands are party to the convention. Although there are numerous sub-Antarctic sites that *prima facie* qualify as important wetlands, including for waterbirds, no sub-Antarctic properties have been listed. Nevertheless, nominations are expected.

CITES

CITES (Convention on the International Trade of Endangered Species of Wild Fauna and Flora 1973) seeks to ensure that trade does not threaten the survival of species. All sub-Antarctic states are party to the Convention. Various species of marine mammals present in the sub-Antarctic region are listed in Annex II of CITES, including several species of seals and dolphins.

MARPOL

MARPOL 73/78, which comprised the convention and its subsequent protocol (International Convention for the Prevention of Pollution from Ships 1973 as Modified by the Protocol of 1978 Relating Thereto 1978) addresses marine pollution throughout the world's oceans and entered into force on 2 October 1983. All sub-Antarctic states are party to both instruments. Subsequently, numerous subsidiary annexes and amendments have been added to this now well-developed regime, but there is not enough space here to provide a detailed survey of which states are parties to each of them. One of the affiliated conventions deals with ballast water, an issue which is addressed below.

Convention on Biological Diversity

The Biodiversity Convention (Convention on Biological Diversity 1992) seeks to conserve biological diversity and regulate sustainable use while allowing equitable sharing of benefits. All sub-Antarctic states are party to the Convention. The Convention allows the establishment of protected areas where special measures can be taken to conserve biological diversity. In Australia's case, the Heard Island and McDonald Island Marine Reserve assists Australia meets its obligations under the Convention.

OTHER INTERNATIONAL ARRANGEMENTS

Other arrangements that are international in character but do not involve legal instruments also apply in the sub-Antarctic region.

IUCN

IUCN, or World Conservation Union as it is also known (International Union for the Conservation of Nature and Natural Resources 2007), was established in 1948 and acts as a network of states, inter-governmental and non-government organisations to encourage conservation and sustainable use of natural resources. IUCN's particular relevance in the sub-Antarctic region is with respect to protected area management. This is consistent with its objective of promoting a representative network of terrestrial and marine protected areas. IUCN provides advice on world heritage values, and it established the now widely recognised categories of protected areas. IUCN is also interested in high seas management, especially fisheries issues such as bottom trawling.

IUCN maintains the Red List or the world's vulnerable, threatened and endangered species — these include sub-Antarctic species such as albatrosses threatened by long-line fishing.

UNESCO

UNESCO is a long-established agency of the United Nations. UNESCO's inter-disciplinary Man and Biosphere Program provides for a unique category of protected area (United Nations Educational, Scientific and Cultural Organization 2007). Biosphere Reserves are designated as important areas for conserving biological diversity and furthering scientific knowledge. Macquarie Island was listed as a Biosphere Reserve in 1977 and, to this point, remains the first and only true sub-Antarctic site to be so designated (although there is a Biosphere Reserve at Cape Horn, which is at a comparable latitude). As UNESCO Biosphere Reserves are primarily directed towards areas where conservation objectives need to be balanced against sustainable development interests, it is unlikely that in the near future there will be further designation of Biosphere Reserves in the remote and isolated sub-Antarctic region where sustainable development issues are not a current concern.

SCAR

SCAR is an inter-disciplinary committee of the International Council of Science (Scientific Committee on Antarctic Research 2007). Its role is to coordinate high-quality international research in the Antarctic region. SCAR, while not formally constituted as such, is often regarded as a *de facto* component of the Antarctic Treaty system even though its mandate goes well beyond the Antarctic Treaty area. SCAR has a broad interest and thus, while having a focus on the Antarctic Treaty area, takes a keen interest in Southern Ocean research more generally and science that is conducted on the sub-Antarctic islands. Some SCAR-endorsed science programs conduct research across the Antarctic and sub-Antarctic regions. All of the sub-Antarctic states are members of SCAR and contribute to the research programs that it endorses.

IPY

An international polar year (IPY) has previously been celebrated in 1882/83, 1932/33, and 1957/58. The 4th IPY (International Polar Year 2007) covers research in both the Arctic and the Antarctic. It also includes research in the sub-Antarctic region. While limited to a two-year period,

IPY was planned on the basis of leaving a legacy of enhanced international scientific collaboration.

Bilateral cooperation

As examples of bilateral cooperation arrangements, JAMBA (Agreement between the Government of Australia and the Government of Japan for the Protection of Migratory Birds in Danger of Extinction and their Environment 1974) and CAMBA (Agreement between the Government of Australia and the Government of the People's Republic of China for the Protection of Migratory Birds and their Environment 1986) are agreements respectively between Australia and Japan and China on the protection of migratory birds. These two agreements, which are limited to those specific bilateral relationships, provide for cooperation on the management and protection of migratory birds. Heard Island includes species which are subject to the agreements with Japan and China. There may emerge other bilateral cooperation agreements between sub-Antarctic states which have implications for the management of the sub-Antarctic islands.

SUB-ANTARCTIC ACTIVITIES THAT ARE NOT INTERNATIONALLY REGULATED

Many activities in the sub-Antarctic are not regulated by international instruments. Tourist interest in the sub-Antarctic region continues to grow. Sub-Antarctic islands currently have their own regimes for controlling tourist access and managing their activities on the ground. There may be merit in developing consistent tourism management measures for the sub-Antarctic islands and, given that sub-Antarctic sites are often visited in conjunction with visits to Antarctica, there is an opportunity to harmonise them with the emerging regulations for the Antarctic region. This could include guidelines on visitor behaviour near wildlife or sensitive vegetation, safety standards, self-sufficiency and insurance.

Quarantine matters are not internationally regulated for the sub-Antarctic islands. Each sub-Antarctic state implements its own domestic requirements either through legislation, permit conditions, training or other administrative mechanisms and, as Potter (2007) points out, arrangements can differ even for sub-Antarctic islands belonging to the same country. The importance of addressing the quarantine issue is underlined by the known sensitivity of some sub-Antarctic sites to new introductions as well as, at some sites, by the paucity of scientific assessments of the natural reference state.

MARPOL already addresses waste disposal and pollution from ships. However, there may be scope for specific measures to be internationally agreed for sub-Antarctic islands and adjacent waters where there are particular vulnerabilities in the marine and terrestrial ecosystems.

The Ballast Water Convention (International Convention for the Control and Management of Ships' Ballast Water and Sediments 2004) has not yet entered into force. This convention is part of the MARPOL family. To this point there are only six parties, covering less than 1% of ship tonnage globally. The convention requires that, where possible, ballast water should be exchanged more than 200 nautical miles from the nearest land and in water over 200 metres deep. Otherwise it should be done more than 50 nautical miles from land. Where these circumstances cannot be met then areas can be designated for ballast water discharge. A Party or Parties may impose additional measures to prevent or reduce the transfer of harmful aquatic organisms.

The 2006 Antarctic Treaty meeting adopted a resolution and guidelines on the management of ballast water in the Antarctic (Antarctic Treaty 2006). To further reduce the risk of introducing invasive marine species in the sub-Antarctic, there is merit in special management measures for the sub-Antarctic islands to achieve consistency with the Antarctic regime, and consistency between sub-Antarctic islands. It is arguable that the sub-Antarctic islands are at least as vulnerable as Antarctic waters to the introduction of marine pests, especially so since every ship travelling to the Antarctic has to pass through the sub-Antarctic.

POSSIBLE FUTURE INTERNATIONAL ARRANGEMENTS

There is potential for further international arrangements, but this paper does not argue the case for new *legal* instruments unique to the sub-Antarctic — they are not necessary. However, there is a strong argument for developing cooperative approaches to addressing the region's management challenges.

As noted above, the Antarctic Treaty provides a robust, stable and effective consultative mechanism to develop management approaches in Antarctica. However, there is no comparable ongoing international mechanism within which to exchange information about the sub-Antarctic region and to develop consistent procedures. Apart from the 2006 forum in Tasmania, there have been previous workshops under the auspices of SCAR and IUCN, but these have been intermittent. Considerable benefits could be achieved by putting in place a regular, structured forum or network for the exchange of views about sub-Antarctic issues, including environmental management issues.

Such a forum or network would be based on the common values of the sub-Antarctic region — the oceanic marine environment; the values of the island ecosystems; the scientific opportunities; the cultural values; and the outstanding natural values.

POSSIBLE NEW INITIATIVES

A regular and structured forum or network would also facilitate the exchange of ideas and expertise on management of the sub-Antarctic region, especially the islands which are already facing significant environmental issues.

Matters that could usefully be explored and have agreed procedures developed include:

- management of tourism, with a particular emphasis on developing consistent rules of behaviour to apply to visitors at all islands
- consistent quarantine procedures: for example, there would be value in shared development of mechanisms for preventing or responding to introduced species (this could be particularly useful at places like Heard Island, which is one of the places with the lowest number of non-indigenous species, but whose closest neighbour is Îles Kerguelen, which has one of the highest numbers of alien introductions)
- regional responses to fuel spills, including measures for

cooperative responses and exchange of information and experience with response
- special arrangements that may need to be made with respect to safety of shipping in poorly chartered waters, or safety of distant water sailors and fishers who may operate in the vicinity of sub-Antarctic islands
- a case could possibly be made for declaring the sub-Antarctic islands, as a group, as MARPOL special areas (e.g., for waste disposal or ballast water handling)
- a mechanism for the timely exchange of scientific data, including a capacity to inform SCAR and national program scientists what research needs to be done to inform management decisions
- exchange of environmental management information: this could lead, for example, to a state of the environment reporting process for the sub-Antarctic
- coordination of scientific research in the sub-Antarctic region after the conclusion of IPY, in consultation with SCAR and focused on sub-Antarctic research priorities
- monitoring, particularly on the unoccupied islands where there is scant available information, but also monitoring which will inform management of the sub-Antarctic islands individually and as a group
- exchange of information on opportunities for logistic cooperation: this could have the effect of extending to the sub-Antarctic region the kind of cooperation achieved under COMNAP (Council of Managers of National Antarctic Programs 2007) in Antarctica.

A regular forum or network would also provide a mechanism to develop proposals that can be taken into other international forums and instruments, or to inform domestic policy making and regulatory mechanisms in a way which is consistent across the relevant jurisdictions. A forum could also be used to provide a context for making the case for funding programs in the sub-Antarctic islands which often have to compete with funding for higher profile activities in the Antarctic.

It is often observed that the sub-Antarctic islands are among the areas more susceptible to climate change. For example, the glaciers of Heard Island (which is close to the Antarctic Polar Front) have been observed to be particularly sensitive to warming. An international network could help prepare common responses to environmental changes that may occur — for example, this could include monitoring in areas which are particularly sensitive to climate change and the development of procedures that assist in dealing with the environmental consequences of change.

A sub-Antarctic forum or network could be supported by a website devoted to matters of common interest across the sub-Antarctic region, and funded by modest national contributions.

CONCLUSIONS

Unlike the Antarctic, the sub-Antarctic region does not require a special international regime — and, in all likelihood, it could be very difficult to negotiate one. The jurisdictional situation allows effective use of domestic legal regimes and there is good evidence that domestic regimes have considerable rigour.

However, and possibly as a result, there is inconsistent use of legal instruments in the sub-Antarctic. Nevertheless, there is increasing application of the various international instruments, most particularly in the area of environmental management. While the application of the instruments continues to evolve, these developments are not happening in a coherent or integrated way. This should not be seen as a negative. But it does point to an opportunity for greater international collaboration which may encourage consistency between the states with sub-Antarctic interests. In particular, there may be value in more regular forums for an exchange of views on topical environmental and management issues. This can be complemented by developing a network of managers, scientists and policy makers to advance the issues that are unique to the sub-Antarctic region.

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CONSERVATION AND MANAGEMENT FRAMEWORKS FOR SUB-ANTARCTIC INTERNATIONAL WATERS

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The waters of the sub-Antarctic Southern Ocean are legally distinctive from those which fall within the Antarctic Treaty area extending to 60°S, not only because the Treaty does not apply in those waters but also because sovereignty over sub-Antarctic islands is largely uncontested. As a result, many of the countries claiming sub-Antarctic possessions are able to assert the full range of maritime claims, resulting in sub-Antarctic waters being a mixture of state-controlled waters and those which fall under either international fisheries regimes such as the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) or are high seas. Conservation and management of sub-Antarctic waters other than with respect to fishing have not received the same priority as they have in waters around the continent. However, the same issues arise and are in fact magnified due to the greater accessibility of the northern reaches of the Southern Ocean and potential for greater environmental and resource impact. The extent of the international waters of the Sub-Antarctic Southern Ocean is clarified here, the applicable international management regimes are reviewed and the contemporary issues confronting the region are considered. Proposals are considered for enhanced internationalisation of the region.

Key words: sub-Antarctic legal regimes, sub-Antarctic bioprospecting, sub-Antarctic maritime claims, Southern Ocean management, Southern Ocean environmental protection, sub-Antarctic fisheries regulation, sub-Antarctic "international waters".

INTRODUCTION

Primarily as a result of the application of the 1959 Antarctic Treaty the waters of the sub-Antarctic Southern Ocean are legally distinctive from that part of the Southern Ocean which encircles the Antarctic continent. The impact of Article IV of the Treaty was to place legal constraints upon the active assertion of new maritime claims within the Antarctic Treaty area. In addition, even if such claims were asserted, the ability to actually enforce national laws and regulations regulating resource management or environmental protection was compromised by the provisions of Article VIII of the Treaty. The result has been that whilst some Antarctic Treaty claimants such as Australia have been proactive in the assertion of a range of maritime claims offshore from their Antarctic territories (Kaye & Rothwell 2002), the claims are not widely recognised and in some instances are actively contested (Rothwell & Scott 2007). This is not the case with respect to those sub-Antarctic waters north of 60°S beyond the outer limits of the Antarctic Treaty. In that part of the Southern Ocean sovereignty over sub-Antarctic islands is by and large not contested and accordingly the claimant states are not limited in their capacity to assert the full range of maritime zones, including 200-nautical-mile Exclusive Economic Zones (EEZ) and continental shelves, and in some instances claims which extend some distance beyond that limit (Jabour 2006). This provides for some certainty in determining which parts of the sub-Antarctic may truly be characterised as "international" in nature — that is waters beyond the reach of national jurisdiction which are either high seas or deep sea-bed, consistent with the provisions of the 1982 United Nations Convention on the Law of the Sea (LOS Convention).

The only part of the sub-Antarctic subject to a regional marine management framework is that over which the 1982 Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) extends. The "international management" of these sub-Antarctic waters ensures a complementarity with those Southern Ocean waters south of 60°S, but has also created certain challenges for those states claiming islands within the region and seeking to actively regulate and enforce their fishery laws consistent not only with CCAMLR but also with their own national laws (Haward 2004). The sub-Antarctic is also subject to a range of other international management mechanisms ranging from international treaties and regimes dealing with whaling, to biodiversity conservation, to multiple forms of marine pollution, and deep sea-bed management. One of the challenges is reconciling the interests of the international community in managing these waters, with the regional interests of states who are parties to the Antarctic Treaty and CCAMLR, and with individual and distinctive national interests on the part of the sub-Antarctic states. This paper clarifies the extent of the international waters of the sub-Antarctic Southern Ocean, reviews the applicable international management regimes, and considers the contemporary issues confronting the region. Proposals are considered for enhanced internationalisation of the region.

INTERNATIONAL WATERS IN THE SUB-ANTARCTIC

Identifying international waters

Much of the modern law of the sea is directed towards confirming and clarifying the extent of coastal state sovereign rights and jurisdiction over adjacent maritime areas (Churchill & Lowe 1999). Commencing with the territorial sea, over which coastal states have almost exclusive sovereign rights and jurisdiction subject only to the freedom of navigation by foreign ships, the law of the sea recognises a mix of sovereign rights and jurisdiction over adjacent maritime areas which extend to the outer edge of the continental shelf. Resource sovereignty is recognised over the water column, seabed and subsoil up to the limit of the 200-nautical-mile EEZ (LOS Convention, Article 56). However, beyond that limit it is

possible for sovereign rights to be projected in the case of an extended continental shelf up to approximately 350 nautical miles from the coast (LOS Convention, Articles 76, 77).

The law of the sea (LOS) recognises that beyond the outer reaches of coastal state maritime zones there exist other maritime zones which are either subject to "international" control or may truly be classified as *res communis* — that is the area belonging to no single state and to which all enjoy rights of equal access (Churchill & Lowe 1999). The first is the high seas which is the water column including the surface beyond the limit of the 200-nautical-mile EEZ. High seas freedoms are some of the most historic rights recognised under international law and traditionally extend to freedom of fishing and freedom of navigation (LOS Convention, Part VII). Under the modern law of the sea, they also extend to the freedom to conduct marine scientific research (LOS Convention, Article 87). The other regime is that dealing with the deep sea-bed, which is the "Area" beyond the limits of national continental shelf claims.

Some of the complexity that exists in identifying the international waters of the sub-Antarctic Southern Ocean are highlighted in the case of the deep sea-bed. The LOS Convention provides that "The Area and its resources are the common heritage of mankind" (Article 136) and are effectively subject to an international regime under Part XI of the Convention which confers responsibility upon the International Sea-bed Authority (ISBA) for management of the area (Joyner 1986). However, under Article 1 of the LOS Convention the "Area" constitutes that part of the sea-bed and ocean floor which is "beyond the limits of national jurisdiction"; that being the sea-bed and ocean floor which is not subject to any sovereign rights or jurisdiction of any state. Ascertaining what part of the sea-bed and ocean floor exists beyond the limits of national jurisdiction is made complex because of the capacity of coastal states to assert extended continental shelf claims. However, there is no unilateral right to assert such a claim. The LOS Convention provides that coastal states seeking to assert an extended continental shelf claim must first make a submission to the Commission on the Limits of the Continental Shelf (CLCS) which will make "recommendations" to the coastal state on matters relating to the claim. On the basis of those recommendations, the coastal state will be able to make a final claim to an extended continental shelf. Only once all potentially eligible coastal states have asserted extended continental shelf claims will the full extent of the ISBA's jurisdiction over the Area be settled.

Sub-Antarctic maritime claims

In reviewing sub-Antarctic maritime claims so as to identify by default that area of the sub-Antarctic Southern Ocean which may properly be identified as "international waters", it is important to distinguish the area north of 60°S from that to the south. That part of the Southern Ocean governed by the Antarctic Treaty up to 60°S raises a multitude of issues as to whether, under the Treaty, there are recognisable "coastal states", how baselines may be asserted around an ice-fringed continent, how new maritime zones can be asserted consistently with the modern law of the sea and the Antarctic Treaty's limitations on the assertion or enlargement of claims, in addition to the enactment and enforcement of laws and regulations which may apply to regulate activities in those maritime areas (Oude Elferink & Rothwell 2001). None of these issues exists to the same extent in the sub-Antarctic, thereby freeing all of those states who claim sub-Antarctic possessions to assert all potential maritime claims under the law of the sea.

The various sub-Antarctic states have sought to assert the full range of maritime claims to which they are entitled under the current law of the sea. Some, such as fishing zones or EEZs, are relatively uncontroversial other than in the case of where sovereignty over the islands may be contested (e.g., South Georgia where the United Kingdom and Argentina remain in dispute (Orrego Vicuña 1996)). There is also a number of asserted claims which because of their apparent inconsistency with the LOS Convention and contemporary international law remain controversial, such as Chile's assertion of a "Presential Sea" (Orrego Vicuña 1992). Presently, one of the most contentious issues with respect to sub-Antarctic maritime claims relates to assertions of an extended continental shelf (Oude Elferink 2002).

Of the sub-Antarctic nations, Australia has perhaps been the most prominent in terms of its assertion and enforcement of maritime claims. Australia's position in terms of its sub-Antartic possessions — the Heard and McDonald islands, and Macquarie Island — is influenced by its position more generally with respect to maritime claims offshore the Australian Antarctic Territory (AAT). Australia has asserted a range of claims offshore the AAT which the government considers to be consistent with both its obligations under the Antarctic Treaty and the LOS Convention (Kaye & Rothwell 2002). Australia first asserted a continental shelf claim offshore the AAT in 1953. In 1973 Australia proclaimed a three-nautical-mile territorial sea around all its territory, including the AAT, and in November 1990 extended this from three to 12 miles. Australia proclaimed an EEZ off the AAT on 1 August 1994 (Opeskin & Rothwell 1991). Yet, Australia has adopted the somewhat ambiguous legal position of having asserted these maritime claims without actively implementing its laws within these zones. Whilst a good deal of Australian law applies within these various maritime areas offshore the AAT, there has been no instance of such law being applied to the activities of non-Australian nationals or foreign vessels. Australia has thereby sought to maintain the integrity of its claim to sovereignty over the AAT and the accompanying maritime sovereignty and jurisdiction which any coastal state enjoys over its offshore areas, whilst also respecting the limitations on the active assertion of sovereignty and jurisdiction imposed by the Antarctic Treaty.

In November 2004 Australia submitted an extended continental shelf claim to the CLCS (Downer, Ruddock & Macfarlane 2004) which has implications for the Southern Ocean. The Australian claim will, if accepted by the CLCS, give to Australia a continental shelf of approximately 3.4 million square kilometres, which when combined with its land territories will make it one of the largest States in the world. Australia has relied upon its sub-Antarctic possessions as part of the foundation for its extended continental shelf claim in the Southern Ocean. In the Kerguelen Plateau region, Heard Island and the McDonald islands are the landmasses from which the extended continental shelf claim is based. In the Macquarie Ridge region, the Australian claim extends south from Macquarie Island to encompass an area 81719 km^2 beyond the 200-nautical-mile edge (Commonwealth of Australia 2004). Both of these asserted claims extend south beyond 60°S into the Antarctic Treaty area.

The extended continental shelf claims from the Heard and McDonald islands, and Macquarie Island, may raise some concerns as to their legitimacy given the islands have no permanent population and in the case of the Heard and McDonald islands are uninhabited other than for an occasional visit by research scientists and tourists. This is significant, as Article 121 of the LOS Convention suggests that islands not capable of sustaining human habitation or an economic life of their own are more properly classified as rocks than islands and thereby not entitled to generate a claim to a continental shelf or EEZ (Kwiatkowska & Soons 1990). Judge Vukas has already expressed his concerns in the International Tribunal for the Law of the Sea (ITLOS) regarding the legitimacy of the Australian EEZ offshore these islands (The Volga Case 2002). However, given the size of the islands and the "economic life" they have generated as a consequence of Australian licensed fishing activities in those waters (principally for Patagonian Toothfish) it is difficult to sustain a credible argument that Australia is not entitled to seek to assert an extended continental shelf. That the Australian claim purports to extend into the Antarctic Treaty area is of more significance. For Australia this raises some delicate issues under the Antarctic regime, especially with respect to the prohibition contained in the Antarctic Treaty, Article IV, on the assertion of any "new claim, or the enlargement of an existing claim, to territorial sovereignty in Antarctica" while the Treaty is in force (Kaye 2001a).

Australia has also sought to assert an extended continental shelf claim offshore the AAT. The claim seeks to enclose an area of 686 821 km^2 beyond the limits of the 200-nautical-mile EEZ (Commonwealth of Australia 2004). However, recognising the sensitivity that the assertion of such a claim raises for the international community and under the Antarctic Treaty, Australia requested that the CLCS not "take any action for the time being" with respect to that part of the claim offshore the AAT with the effect that the claim is effectively set aside for the time being (Jabour 2006). Nevertheless, the Australian claim generated an interesting response from other Antarctic Treaty parties, with six — Germany, India, Japan, Netherlands, Russian Federation, and the United States — all lodging communications with the Secretary-General of the United Nations. Each of the communications makes direct reference to the provisions of the Antarctic Treaty, particularly Article IV, and denies recognition to rights or claims over the seabed or adjacent offshore surrounding Antarctica (Rothwell & Scott 2007). Interestingly, the only communication relating to the Australian claim from another sub-Antarctic state was from France, and whilst the French communication does refer to the Australian claim off the Kerguelen Plateau it does not contest Australia's capacity to make such a claim (France 2005).

In 2006, New Zealand lodged a claim for an extended continental shelf. Unlike the Australian claim noted above, it excludes a claim offshore the Ross Dependency though New Zealand has reserved its position to make such a claim at a latter point in time (New Zealand 2006a). New Zealand does rely though upon Campbell Island as the basis for an extended continental shelf in the sub-Antarctic with the claim extending as far south as 57°34'S (New Zealand 2006b).

The CLCS now has both the Australian and New Zealand extended continental shelf claim under active consideration. The role of the CLCS is briefly referred to in the LOS Convention, Article 76(8) where reference is made to the need for coastal states to submit information on their extended continental shelf claims to the Commission. The Article then goes on to provide: "The Commission shall make recommendations to coastal States on matters related to the establishment of the outer limits of their continental shelf. The limits of the shelf established by a coastal State on the basis of these recommendations shall be final and binding." This rather brief provision in the LOS Convention therefore creates a quasi-judicial process in which the CLCS is effectively the "legitimator" of a coastal state's claim (McDorman 2002). The outcome of this process is the establishment of outer continental shelf limits which will have implications for the Part XI deep sea-bed regime and importantly for current purposes help to define those parts of the sea-bed which fall within sovereign jurisdiction under the continental shelf regime. It is beyond those areas — beyond the limits identified by coastal States following consultation with the CLCS — that the international sea-bed will exist. Whether other sub-Antarctic claimants seek to assert extended continental shelf claims offshore their possessions remain to be seen. In principle there is nothing to stop the other states doing so, other than where there exists disputed sovereignty, as is the case with South Georgia, or where the extended claim overlaps that asserted by another state as may arise between Australia and France in the Kerguelen Plateau.

CCAMLR and the sub-Antarctic

The CCAMLR regime extends north of 60°S so as to legitimately operate across the sub-Antarctic waters of the Southern Ocean. Whilst the operation of the Convention within the Antarctic Treaty area is uncontroversial given the consistency of the two legal regimes, this is not the case in the sub-Antarctic given the mixture of coastal state claims asserted offshore the islands mixed with international waters which truly fall beyond the limits of national jurisdiction. This issue was anticipated at the time of CCAMLR's negotiation and an attempt was made to harmonise the CCAMLR fisheries management regime with any fisheries laws and regulations that may have been or would be enacted in the future by sub-Antarctic claimant states (Kaye 2001b). The result was the so-called "bifocal approach" under which the laws and regulations adopted by sub-Antarctic states would continue to apply within their fishery zones and EEZs only if they expressly sought to exempt themselves from the application of relevant CCAMLR provisions (Orrego Vicuña 1996), thereby permitting those sub-Antarctic States with potential for significant fishing activities to either apply the CCAMLR regime or opt out. Notwithstanding this capacity, the practice of the principal sub-Antarctic fishing States such as Australia and France has been to work within the CCAMLR regime and indeed to actively rely upon it in their efforts to counter "Illegal Unregulated and Unreported" (IUU) fishing (Haward 2004), whilst at the same time developing management plans to ensure a sustainable fishery (Abetz 2006).

What are the international waters of the sub-Antarctic?

On the basis of the above review the following can be concluded with respect to identifying the international waters of the sub-Antarctic. With respect to the water

column, the area includes all waters over which CCAMLR extends north of 60°S in addition to those waters properly classified as high seas. In relation to the sea-bed and ocean floor area of the sub-Antarctic, that part which can truly be classified as "international" remains subject to finalisation once determinations have been made by the CLCS on extended continental shelf claims and the sub-Antarctic states have formally proclaimed their extended continental shelves beyond the 200-nautical-mile limit. It may in fact take some time before the "Area" which falls within the Southern Ocean is conclusively determined; nevertheless the LOS Convention does place a time limitation upon the making of extended continental shelf claims (LOS Convention, Annex II) and whilst there has been some modification of that process the sub-Antarctic states do not have unlimited time in which to assert their claims. That both Australia and New Zealand have submitted their Southern Ocean claims in recent years suggests there is a growing momentum amongst the sub-Antarctic states to resolve these matters soon. Only once that process is complete will it be possible to determine conclusively the "international waters" of the sub-Antarctic.

Managing sub-Antarctic international waters

The management of sub-Antarctic international waters is subject to numerous international and regional regimes. Historically, the most prominent of these regimes has been CCAMLR and as noted above this Antarctic Treaty System (ATS) instrument is unique because not only does it apply beyond the Treaty limit of 60°S to truly extend into the sub-Antarctic, but it also seeks to harmonise its provisions with the laws and regulations adopted by sub-Antarctic states. The other body whose jurisdiction is uncontested but which has yet to become truly operative is ISBA. Whilst the ISBA was one of the first institutions established under the LOS Convention, its effectiveness has been delayed somewhat until such time as the boundaries of the "Area" have been conclusively determined. Therefore, whilst theoretically the ISBA has management capacity over the sea-bed and ocean floor of the sub-Antarctic Southern Ocean, it may be some time until it actually exercises that capacity. It must be anticipated though that at some time in the future there will be interest in the exploration and exploitation of the sub-Antarctic sea-bed which will inevitably raise environmental issues and the compatibility of such activities with the prohibition on mining under the 1991 Protocol on Environmental Protection to the Antarctic Treaty (Madrid Protocol) which applies within the Antarctic Treaty area (Scovazzi 1996).

In addition to these specialist regimes for the Antarctic and the oceans, there exists an additional body of international environmental law with global, regional and sub-regional application of relevance to the sub-Antarctic. Whilst international environmental law is a relatively new area of international law (Birnie & Boyle 2002), the Southern Ocean has long been subject to its application especially through the 1946 International Convention for the Regulation of Whaling (Whaling Convention). Through a range of "hard law" binding treaties such as the 1972 World Heritage Convention, 1973 International Convention for the Prevention of Pollution from Ships (MARPOL) and the 1992 Convention on Biological Diversity, many Southern Ocean activities have become subject to environmental regulation thereby complementing the environmental management provided for under the ATS (Rothwell 2004).

A number of these regimes has raised particular issues for the Southern Ocean generally and the sub-Antarctic more specifically. An impact of increased fishing activities under CCAMLR has been the phenomenon of seabird bycatch. This proved to be the catalyst for adoption in 2001 of a special agreement between several sub-Antarctic states dealing with conservation of albatrosses and petrels (Hall 2007). Whaling has a long history in the Southern Ocean, with respect to a vibrant industry in the nineteenth and early twentieth centuries and more recently for conservation and sustainable management of whale stocks. Under the provisions of the 1946 Whaling Convention, commercial whaling has been prohibited since the 1985/86 season and in addition a "Southern Ocean Whale Sanctuary" has been adopted, the effect of which is to permanently prohibit all commercial whaling in the Southern Ocean in an area which in parts extends as far north as 40°S. This Sanctuary is complemented by an "Indian Ocean Sanctuary" which extends as far south as 55°S in the Indian Ocean, thereby creating an extensive area of the Southern Ocean and adjacent waters within which all commercial whaling is prohibited.

There is currently controversy over whether the activities of Japan in the Southern Ocean are in breach of the Whale Sanctuary due to Japan's authorisation of "scientific whaling" of minke, fin and humpback whales. While Japan contends that these activities are consistent with the exemption for "scientific whaling" under the Whaling Convention, Australia and New Zealand have been actively engaged in a campaign opposing Japan's activities which has resulted in legal action being taken in the Australian courts (Blay & Bubna-Litic 2006). Whilst to date this controversy has not had a particular sub-Antarctic focus, it does highlight the potential for disagreement over management and conservation efforts in the Southern Ocean more generally, notwithstanding the existence of the Southern Ocean Whale Sanctuary.

Controversy has also flared due to the overlap of certain resource management regimes. For example, in 2005 it was revealed that southern bluefin tuna were being harvested within the CCAMLR area of the Southern Ocean under the authorisation of a commission created under the 1993 Convention on the Conservation of Southern Bluefin Tuna. This instance of "regime overlap" highlighted the need for greater harmonisation between the various institutions with capacity for regulating fisheries in the sub-Antarctic and the potential for effective resource management to be compromised unless the institutions resolve their areas of competency and seek to minimise management conflict (Hemmings 2006). Whilst the waters of the Southern Ocean and sub-Antarctic are also the subject of multiple International Maritime Organisation (IMO) conventions and treaties regulating maritime affairs including shipping movements, marine pollution, and liability and compensation, doubts have been raised as to the adequacy of these mechanisms. These doubts centre on whether they are capable of resolving maritime disasters in the Southern Ocean given the inevitable environmental impact which will arise from such events (Zovko 2005). This is especially an issue in the light of growing vessel traffic in the region arising from tourism demand and the increased proliferation of icebergs in sub-Antarctic waters. The management of sub-Antarctic international waters is therefore the subject of multiple international and regional legal regimes. Whether they all operate in harmony is questionable.

CURRENT CHALLENGES IN THE MANAGEMENT OF SUB-ANTARCTIC WATERS

Having identified the international waters of the sub-Antarctic, what are some of the current issues facing the management of these waters? The most prominent at present include bioprospecting and marine scientific research, and IUU fishing.

Bioprospecting and marine scientific research

Bioprospecting has been the subject of a number of definitions. However, it can generally be considered "a scientific exploring activity to search for something useful from nature" (Farrell & Duncan 2005 p. 13). There has been of course an historical interest in scientific research activity in Antarctica and the Southern Ocean and indeed it is upon this foundation that the Antarctic Treaty was partly founded. Whilst there has always been a commercial element to Antarctic research, bioprospecting both on the continent and within the Southern Ocean takes this issue to another dimension given the potential commercial benefits to be reaped from certain discoveries. The conduct of bioprospecting in Antarctica and the Southern Ocean is therefore an activity which has generated considerable interest in the past decade (Jabour-Green & Nicol 2003, Hemmings & Rogan-Finnemore 2005).

Pivotal to an understanding of the legal regime dealing with marine bioprospecting are the provisions of Part XIII of the LOS Convention dealing with marine scientific research (Guyomard 2006). Part XIII makes clear that all states have a right to conduct marine scientific research subject to the rights and duties of other states, including coastal states (Article 238). The framework which is then constructed, is as follows:

- Within the Territorial Sea the coastal state has the exclusive right to regulate marine scientific research meaning that the activity can be either prohibited, or permitted subject to regulation (Article 245).
- Within the EEZ and continental shelf the coastal state can regulate marine scientific research on the basis that in normal circumstances consent will be granted for such research to be undertaken by other States (Article 246).
- In the Area and within the water column beyond the 200-nautical-mile limit, all States have the right to conduct marine scientific research (Article 256-257).

Taking into account this framework and the provisions of the law of the sea as it applies to the Southern Ocean discussed above, the following can be concluded:

- that within the Southern Ocean, sub-Antarctic States have a capacity to proclaim maritime zones
- sub-Antarctic States have the capacity to explore and exploit the water column and sea-bed
- sub-Antarctic States can legitimately seek to determine the outer limits of their continental shelf claims
- sub-Antarctic States can likewise seek to regulate marine scientific research within their adjacent territorial sea and EEZ/continental shelf areas
- that parts of the Sub-Antarctic Southern Ocean may be considered to be part of the "Area" and fall under the Part XI deep sea-bed regime (Oude Elferink & Rothwell 2001, Joyner 1992).

Given the unique legal regime that exists in the Southern Ocean as discussed above, a legal regime for bioprospecting in the sub-Antarctic Southern Ocean could revolve around the following actors. First, coastal states play a key role as recognised by the marine scientific research provisions of Part XIII of the LOS Convention. They have a clear-cut capacity to regulate bioprospecting within the narrow 12-nautical-mile territorial sea, and further beyond to the limits of the EEZ and continental shelf. Second, so-called flag states (who register ships thereby permitting them to fly the "flag" of that state) play an important role in regulating the activities of their ships engaged in marine scientific research so as to ensure compliance not only with the general provisions of the LOS Convention but also with the 1992 Convention on Biological Diversity (CBD) (Guyomard 2006). In addition, flag states also have an important role in ensuring their ships meet the stringent marine environmental provisions which apply within the Southern Ocean including under MARPOL and the Madrid Protocol. Third, there is also a role for the international community more generally especially as envisaged under the CBD but also under the provisions of the LOS Convention dealing with the deep sea-bed and the regulation of activities in the "Area" by the ISBA. Here the role of the Conference of Parties (COP) to the CBD and the growing significance of the meetings of the State Parties to the Law of the Sea (SPLOS) should not be ignored (Oude Elferink 2004). Yet while these groups may comprise the major "players", there remain significant legal challenges in adequately reflecting their interests and ensuring a harmonious legal regime.

Whilst marine bioprospecting will in the majority of instances around the world either be regulated by coastal states controlling activities within their maritime zones or by flag states controlling activities on the high seas, there are significant challenges to doing so in the Southern Ocean (Guyomard 2006, Vigni 2006). This principally arises because of the variable state of the legal regimes which currently apply in the sub-Antarctic and the limited capacity many of the sub-Antarctic states have to enforce their laws and regulations which also arises in the context of fisheries matters (Molenaar 2001). What alternatives then exist to a possible legal vacuum throughout the sub-Antarctic dealing with marine bioprospecting? It could be anticipated that flag state enforcement of bioprospecting laws and regulations would be an adequate alternative. However this also does not present any guarantee for regulation or control of bioprospecting. Given that marine bioprospecting substantially falls under the regulation and control of coastal states within their maritime zones, if flag states do not recognize coastal state sovereignty and jurisdiction but rather consider the Southern Ocean to substantially be high seas and therefore open to all forms of marine scientific research, then the capacity to regulate ships engaged in bioprospecting is further compromised. Indeed, the view could be taken that through a combination of the LOS Convention and the CBD, much of the Southern Ocean could be considered open to bioprospecting and accordingly only subject to the most basic of controls. Under this scenario it could be anticipated that only ATS members states would respect a distinctive Southern Ocean regime regulating bioprospecting.

Further difficulties arise because of the global legal regime created under the CBD and the LOS Convention which promote both marine scientific research and bioprospecting. It could even be argued that given the potential global benefits arising from bioprospecting, such an activity is also generally consistent with the "common heritage" concept

as it applies not only to the deep sea-bed but also to other "commons" such as outer space and the moon. When viewed against the ATS, there is a clear tension between the global regime and the regional as there is currently no framework within the Antarctic regime, the Southern Ocean or the sub-Antarctic to adequately regulate bioprospecting (Johnston & Lohan 2005). Whilst the sub-Antarctic islands represent an exception to the general situation in the Southern Ocean regarding sovereignty and limitations on sovereignty created by the Antarctic Treaty, because of their remoteness and difficulty in enforcing relevant laws and regulations, they also fall within an effective legal vacuum.

Given this situation and the growing interest of bioprospectors in the region, it seems clear that the matter is in need of resolution especially as much of the sub-Antarctic Southern Ocean is potentially "deep seabed" for the purposes of the law of sea (Scovazzi 2006). In recent decades the ATS has taken a proactive role in seeking to fill gaps in the Antarctic legal regime prior to those weaknesses being exploited. Bioprospecting would seem to fall within that category and would be consistent with the initiatives taken to regulate the management of both living and non-living resources especially in CCAMLR. The legal vacuum and the need for certainty may also invite other actors in the international community including the SPLOS, the ISBA, or the CBD COP to enter the field in order to resolve these issues.

IUU fishing

Notwithstanding the lengthy operation of the CCAMLR regime within the Southern Ocean and its acknowledged successes, during the past decade the phenomenon of IUU fishing has grown significantly (Baird 2004). IUU fishing is a global phenomenon which in the Southern Ocean is predominately conducted contrary to CCAMLR regulatory mechanisms. When the fishing activity is conducted within the EEZs of sub-Antarctic islands, it also will be in breach of the applicable laws and regulations regulating fishing activities within those waters. The rise in IUU fishing has resulted in considerable attention being given to the issue within CCAMLR and amongst those sub-Antarctic states seeking to protect the sub-regional fishery (Haward 2004). At the institutional level, CCAMLR has sought to respond by the adoption of enhanced measures to monitor fish stocks, vessel movements, and catch reporting data (Baird 2005). In this respect, CCAMLR has been increasingly drawn into what has become a global response amongst multiple regional fisheries management organisations against IUU fishing (High Seas Task Force 2006). The sub-Antarctic states have also been proactive, with Australia, France, New Zealand, and South Africa all individually and collectively seeking to deal with the issue (Abetz 2007). This reflects not only the concern amongst the sub-Antarctic states of illegal activity occurring within their region, but also the increased commercial interest in Southern Ocean fisheries (Batemen & Rothwell 1998).

IUU fishing presents a particular challenge in the sub-Antarctic because of the relatively weak maritime regulation and enforcement mechanisms that within the region. When fishing is conducted under the CCAMLR framework the onus falls upon the flag state to ensure conformity with CCAMLR provisions. However, some flag states are more vigilant than others in the enforcement of their fisheries laws and this leads to uneven practices amongst some CCAMLR members. For non-CCAMLR members, their fishing vessels are able to operate within CCAMLR waters free of the constraints imposed by the Convention so as to effectively result in "unregulated" high seas fishing. Accordingly, the inherent weakness of the CCAMLR regime when dealing with a global industry such as fishing is a major reason why addressing IUU fishing in the region has proven so problematic. Even when IUU fishing is being conducted within sub-Antarctic EEZs that fall under the CCAMLR regime, notwithstanding that theoretically there exists a more viable law enforcement regime, the reality is that many of the sub-Antarctic states lack effective assets to actually enforce the law and bring the illegal fishers to account. This has certainly been the experience of Australia and France in their efforts to police IUU fishing in the waters adjacent to the Heard and Mc Donald islands and Kerguelen Island respectively. Even when arrests have been made, in some cases the legitimacy of the arrest and detention of the crew and vessel have been challenged in the International Tribunal for the Law of the Sea (Rothwell & Stephens 2004).

Gradually the sub-Antarctic states have individually and collectively sought to tackle the problem of IUU fishing in the region. More assets have been deployed in a policing role including fixed-wing aircraft, patrol boats, naval craft, and in some instances specially fitted-out craft designed to be at sea in the Southern Ocean on lengthy patrols (Macdonald & Ellison 2003). For France, its port facilities at Kerguelen have been an asset, whilst Australia with no viable port within the region has been forced to deploy assets to and from the mainland. South Africa and New Zealand, with their sub-Antarctic possessions less distant from their metropolitan territories have been more readily able to deploy patrols within their sub-Antarctic waters. With enforcement capacity significantly compromised in the sub-Antarctic due to climatic and environmental conditions plus the distance from operating bases, it is not surprising that several law enforcement operations against IUU fishers have raised significant legal and policy challenges. Australia, in particular, has been forced on two occasions to engage in long-distance hot pursuit of suspected illegal fishing vessels fleeing the sub-Antarctic; one pursuit ending off the coast of South Africa with the assistance of South African authorities and another ending in the South Atlantic (Molenaar 2004, Letts 2005). In response to these regional maritime enforcement challenges, Australia and France in 2003 entered into a treaty designed to enhance cooperative surveillance in the Southern Ocean, and in 2007 adopted an additional treaty to provide for cooperative enforcement of their respective fisheries laws (Abetz 2007). In addition, there have been ongoing discussions amongst Australia, France, New Zealand and South Africa regarding informal cooperative enforcement and surveillance mechanisms for the region. The result of these initiatives has been a strengthening of the legal enforcement regime to deal with IUU fishing in the sub-Antarctic. However gaps remain in the enforcement regime raising issues as to whether more comprehensive sub-regional enforcement mechanisms are necessary.

CONCLUDING REMARKS

A feature of Antarctica's history including that of the Southern Ocean is that the region has been subject to waves of human exploitation. Initially the interest was driven by whales and seals. Throughout much of the Twentieth century it has been science that has been exploited in Antarctica, whilst more recently the interest has been in Southern Ocean fisheries. Bioprospecting may now be emerging as the new area of interest for the region, and just as all the drivers of human interest in Antarctica and the Southern Ocean have had repercussions for the sub-Antarctic so too will bioprospecting. This review has demonstrated that the sub-Antarctic, similarly to the region south of 60°S within the Antarctic Treaty framework, is subject to numerous overlapping and intersecting legal regimes which operate at a global, regional and national level. This creates a high level of complexity for managing the "international waters" of the sub-Antarctic, yet also provides a level of legal overlay that may not otherwise be possible in such a remote and underpopulated part of the world.

Whilst the legal regime to date has proven itself capable of managing the region despite some deficiencies in enforcement and regulation, there are looming issues on the horizon which may justify a rethink. Bioprospecting has been identified as one of those issues. Global legal frameworks have been established which actively encourage bioprospecting whilst respecting traditional state sovereignty. These frameworks are not easily transposed onto the Southern Ocean. CCAMLR may provide a possible framework for a response to Southern Ocean bioprospecting, otherwise the sub-Antarctic will be faced with a legal regime based predominantly on the freedom of scientific research under the law of the sea and little by way of sub-Antarctic regulation. Other horizon issues need to be considered. The resolution of extended continental shelf claims in the sub-Antarctic will result in greater certainty as to which parts of the sea-bed and ocean floor are under ISBA jurisdiction thereby opening up parts of the region to deep sea-bed mining. Whether such an activity is compatible with the environmental status of the region, and the potential environmental impact such an activity may have within the Antarctic Treaty area is questionable. Here the role of the ATS will be significant because of its capacity to represent the interests of the Antarctic region in international forums and to negotiate with the ISBA a moratorium on sub-Antarctic sea-bed mining activities.

Sub-Antarctic navigation is also a significant horizon issue because of the booming cruise industry and the existing and growing interest in tourist visits to sub-Antarctic islands. These activities not only raise questions of maritime safety and preparedness for search and rescue, but also whether there exist appropriate polar navigation standards in place for the Southern Ocean (Rothwell & Joyner 2001). The increased presence of icebergs in the Southern Ocean as a possible consequence of global warming will also pose additional threats to both commercial and tourist vessels raising issues as to whether those vessels are properly equipped for the conditions. Finally, as with many current global issues there is an international security dimension to be considered. The region has previously been the scene of an international armed conflict during the 1982 Falklands War. Sovereignty disputes in the region, though muted, still remain. The threat of international terrorism cannot be dismissed, especially given the presence of large tourist vessels carrying predominantly Western passengers. All of which raises issues as to whether the sub-Antarctic and the management of its international waters is appropriately addressed under current international frameworks and mechanisms or whether there is a need for a new framework, either as an addition to the ATS or one which has a distinctive sub-Antarctic focus. This will not be an easy issue to resolve. However the fact remains that the issues confronting the region are as significant as those which have faced the Antarctic in the past, and accordingly a coordinated regional response of some form seems appropriate.

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HUMAN IMPACTS ON SUB-ANTARCTIC TERRESTRIAL ENVIRONMENTS

by D. M. Bergstrom and P. M. Selkirk

(with one plate and three tables)

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Sub-Antarctic islands are some of the rarest ecosystems on the planet and therefore are highly significant. Around 200 years of human activities have left a legacy of substantial impacts. We explore these under the collective headings of resource harvesting, local impacts and habitat loss, homogenisation of biota and human-influenced climate change. Past human activities such as sealing and whaling have left seal species still in recovery phases, and infrastructure that continues to break down and pollute the local environment. Modern-day scientific stations have variously-sized footprints of buildings and tracks, and legacies of contaminants, particularly oils spills. On some islands, alien species have established and there is a range of impacts associated with such taxa ranging from transient to extensive, permanent transformation of ecosystems. Such impacts are being confounded by human-induced climate change. By projection, it is expected that both direct and indirect human impact will continue into the future. It is appropriate to plan all future human activity in ways that will minimise further burden on these ecosystems.

Key Words: sub-Antarctic islands, human impacts, homogenisation of biota, climate change, alien species, contaminants.

INTRODUCTION

When considering the range of human impacts on Antarctica, Hull & Bergstrom (2006) discussed four categories: (1) resource extraction and harvesting; (2) local impacts and habitat loss; (3) homogenisation of biota; and (4) human-influenced climate change. Extending their examination northward, we use these four categories to examine human impacts in the sub-Antarctic region. Our focus is principally on terrestrial and limnetic ecosystems, and does not significantly consider birds and seals which spend most of their time in the marine environment.

RESOURCE EXTRACTION AND HARVESTING

Geological resource extraction

To our knowledge, no substantial mining, i.e., extraction of geological resources, for export has occurred or is currently occurring on any sub-Antarctic island. Local small-scale mining for on-island building activities that would be deemed to have "local impact" has occurred at many islands. In addition, at many of the medium-to-large stations, sediments and aggregates for building (such as building sand and aggregate for concrete) have been and are imported for building purposes. Most sub-Antarctic islands are governed by management plans which offer protection of geological as well as biological and cultural values (Whinam *et al.* 2006).

Biological resource harvesting

Biological resources were extensively extracted from sub-Antarctic islands from the late eighteenth to the early twentieth century, harvesting first fur seals, then elephant seals and later penguins. On Macquarie Island the slaughter of fur seals from populations that had existed on the island for at least 8000 years (Bergstrom 1987) led to their local extinction on the island in less than a decade (Shaughnessy *et al.* 1988). We still do not know what species of fur seal was present during sealing times.

On South Georgia, the Antarctic Fur Seal (*Arctocephalus gazella* (Peters, 1875)) was harvested almost to extinction with over a million seals killed by the early 1800s (Weddell 1825 in Boyd 1993). Elephant Seals (*Mirounga leonina* (Linnaeus, 1758)) were also taken during the nineteenth century but had recovered sufficiently by 1909 to allow for a second phase of sealing. From 1952 the industry was carefully regulated and managed sustainably based on scientific information and principles. A detailed quota system of around 6000 adult bulls per year was enforced until cessation of sealing, along with whaling, in 1964–65 (Headland 1984, McIntosh & Walton 2000).

Since sealing ceased, there has been some population recovery on all islands (Boyd *et al.* 1990, Page *et al.* 2003, Hucke-Gaete *et al.* 2004) with a total population growth rate of around 20% per year on most islands at some stage during recovery. On some islands, population recovery is through recolonisation from other islands rather than local breeding. Genetic analyses indicate that Îles Crozet and Macquarie Island have been recently recolonised by female Sub-Antarctic Fur Seals (*Arctocephalus tropicalis* (J.E. Gray, 1872)) from Marion Island and to a smaller extent, from Île Amsterdam, while South Georgia and Bouvetøya were probable sources for populations of Antarctic Fur Seals at Marion and Heard islands (Wynen *et al.* 2000). Recovery of fur seals on Macquarie Island, however, has been slow and complex due to recolonisation by three species (*A. gazella, A. tropicalis* and *A. forsteri* (Lesson, 1828) — New Zealand Fur Seal) and hybridisation between them (Lancaster *et al.* 2006). Rates of hybridisation are now falling, however, due to greater influxes of pure Antarctic and Sub-Antarctic Fur seals and non-random mating.

Biological harvesting impacted coastal and inland terrestrial ecosystems both directly and indirectly. First, the harvesting of seals and penguin from colonies in near-shore

environments would have removed a disturbance factor and provided open habitat for recolonisation by coastal plants. However, harvesting would also have reduced the supply of marine nutrients that penguin and seals deposit on shore as waste. These are subsequently blown inland either as particulate matter or volatilised ammonia (Erskine *et al.* 1998).

Seal colonies progressively recovered, for example on South Georgia from a few tens of individuals at the beginning of the 1900s to over 900 000 by the mid-1980s (Bonner 1985), and from local extinction on Heard Island to around 30 000 in 1993 and 2001 (Page *et al.* 2003). As populations increased, the disturbance factor to the terrestrial environment has been reinstalled. The increase of Antarctic Fur Seals on South Georgia has had a profound impact on local vegetation with destruction from trampling of the dominant tussock grass, *Parodiochloa flabellata* (Lam.) C.E.Hubb., *Deschampsia antarctica* E.Desv. and cryptogamic meadows. Destruction of the tussock has reduced petrel breeding habitat and general loss of vegetation has increased erosion rates (Bonner 1985). Similarly on Heard Island, we have observed numerous plants of *Pringlea antiscorbutica* R.Br. ex Hook.f., calculated to be over 40 years old (D.M. Bergstrom & K. Keifer unpublished data), being destroyed by fur seals as they moved between land and shore. On coastal slopes on Heard Island *Pringlea* occurs in extensive monospecific stands which may be artefacts resulting from release from seal disturbance, and their current destruction may reflect a return to pre-sealing conditions.

LOCAL IMPACTS AND HABITAT LOSS

Footprint of past activities

Many impacts can be categorised as "local impact and habitat loss". Past sealing and/or whaling industrial activities occurred on most of the major islands in the sub-Antarctic. All activities have left some form of legacy in terms of the footprints of occupation, now termed "historic sites". The most prominent cluster in the region is the seven abandoned whaling stations and shore based-facilities on the northeast coast of South Georgia (pl. 1A). Of these, Husvik, Grytviken, Stromness and Leith Harbour were abandoned intact in 1965. Since then there has been limited clean-up (McIntosh & Walton 2000), leaving effectively abandoned industrial sites, complete with asbestos problems in some localities. In 2003 clean-up activities began at Grytviken, including removal of wind-blown building debris, burial of asbestos and the removal of oils from shore tanks and partly submerged whale catchers. Similar work is still needed at other whaling stations but is restricted by lack of funds (Pasteur & Walton 2006). Similarly, the abandoned whaling/sealing station at Port Jeanne d'Arc on Grande Terre of Îles Kerguelen has left a large footprint of old huts and equipment, now partially restored and periodically visited by tourists (pl. 1B).

Other sub-Antarctic sealing and whaling industrial sites have left artefacts such as the remains of huts, cave usage, try pots, work platforms, boilers and digesters and other harvesting paraphernalia. It terms of loss of habitat, many historic sites have been partially reclaimed, overgrown by vegetation (Whinam *et al.* 2004), covered by wind-blown sand and occupied by animals (see pl. 1C). Shipwrecked sailors also left artefacts and evidence of occupation.

Footprint of present activities

Current human activities on sub-Antarctic islands fall into three categories: commercial fisheries, national programs and tourism activities (both through an established industry and private expeditions).

The fishing activity that occurs around most islands has a number of terrestrial impacts. First, marine debris washing up on sub-Antarctic shores (Slip & Burton 1991, Convey *et al.* 2002) included fishing nets, floats and associated plastics such as packaging bands. Between 40% on Heard Island and 30% on Macquarie Island of all marine debris has been interpreted as fishing derived; the balance reflects the global issue of human rubbish circulating in the world's oceans (Slip & Burton 1991). A second impact comes from fisheries by-catch reducing the number of seabirds, notably albatrosses and petrels, that would otherwise breed on the islands, a problem that is being addressed by changes in fishing techniques (Gales 1998, Croxall 1998, McIntosh & Walton 2000). A third potential impact from fisheries is through landings by ships' crews, but this currently has not been investigated.

Impacts from national programs are mainly associated with stations and the hub and spoke footprint that emanates from them including tracks, field camps and field huts. The size of this impact varies with the size of the human population and extent of infrastructure. The largest station, Port aux Français on Îles Kerguelen (pl. 1D), with a population of between 50 and 100 people, has multiple facilities including roads, street lighting, radar fields and a space station. McDonald Island has no human presence or any evidence of human impact, and has not been officially visited since the early 1980s. Table 1 summarises the degree of human infrastructure on the larger islands in the region (see also pl. 1E–H). In general, the size of the footprint of habitat loss by human infrastructure is small compared to the overall size of the islands, but most bases are positioned on the coast and these are usually areas with high population densities of seabirds and seals. For example, the wharf and road to the station at Île de la Possesssion is through a King Penguin (*Aptenodytes patagonicus* Miller, 1788) colony (pl. 1G) and nearby are Wandering Albatross (*Diomedea exulans* Linnaeus, 1758) nesting areas. The station at Macquarie Island is only metres away from Elephant Seal and Rockhopper Penguin (*Eudyptes chrysocome* Hutton, 1879) colonies. Despite the inevitable disturbance that humans bring, these animals still congregate and breed successfully at these sites.

In the sub-Antarctic, the creation and persistence of tracks are dependent on the rate of foot traffic along the tracks and on local environmental conditions, as in cool temperate alpine areas (Whinam & Chilcott 1999). On Macquarie Island trench erosion to rock rubble has occurred in a high-use area of track through feldmark vegetation; and in an area of high traffic through coastal slope vegetation (*Poa foliosa* (Hook.f.) Hook.f. and *Stilbocarpa polaris* (Hombr. & Jacquinot ex Hook.f.) A.Gray on deep peat, the track became eroded to deep muddy trenches and holes (Scott & Kirkpatrick 1994). Active management of such severely eroded sites is essential for long-term impact minimisation (as is now the case at these sites: boardwalk at the feldmark site, traffic control at the coastal slope site, Dixon 2001). Tracks are also pathways for alien species invasion from the station hub to elsewhere (Frenot *et al.* in press).

Regular sub-Antarctic tourism is associated mainly with two islands, South Georgia and Macquarie Island. Minor

PLATE 1

(A) Abandoned whaling station at Grytviken, South Georgia, 2007. Note modern tourist yacht in foreground (photographer: M. Davidson). (B) Abandoned whaling station at Port Jeanne d'Arc, Îles Kerguelen, 2002 (photographer: K. Kiefer). (C) Abandoned trypot covered in vegetation, Spit Bay, Heard Island, 2004 (photographer: K. Kiefer). (D) Buildings at Port aux Français, Îles Kerguelen, 2003 (photographer: J. Deere). (E) New base under construction with associated construction material and containers, Marion Island, April 2006 (photographer: S.L. Chown). (F) Macquarie Island Station, 2007 (photographer: K. Kiefer). (G) Landing beach and infrastructure, Île de la Possession, 2003 (photographer: D.M. Bergstrom). (H) Abandoned station with semi-permanent huts in distance at Atlas Cove, Heard Island, 2003 (photographer: K. Kiefer).

TABLE 1
Summary of current footprint of stations on major sub-Antarctic islands

	Possession	Est	Kerguelen	Heard	McDonald	Macquarie	Sth Georgia	Marion	Prince Edward
Visitation	A	R	A	R	N	A	A	A	R
Permanent station	+	–	+	–	–	+	–	+	–
Permanent roads	+	–	+	–	–	+	+	–	–
Maximum human[1]	<50	0	100	<30[2]	0	<50	30	<100[3]	<20[2]
Fuel Farm	+	–	+	–	–	+	–	+	–
Historic sites	+	–	+	+	–	+	+	+	+
Field huts	+	–	+	+	–	+	+	+	–
Walking tracks	+	–	+	–	–	+	+	+	–
Agriculture	–	–	+	–	–	–	–	–	–
Glasshouse/ hydroponics	+	–	+	–	–	+	–	–	–
Additional infrastructure	–	–	+	–	–	–	–	–	–

A annual, R rare, N none, [1] excluding tourist numbers, [2] periodic visitation, [3] inflated due to rebuilding program. + yes/present, – no/absent.

tourism (fewer than 10 people per voyage) does occur with the French national program to Îles Crozet and Îles Kerguelen. Occasionally tourist ships visit Heard Island and fishing control vessels sometimes have brief landings for management and recreational purposes. On Macquarie Island activities are restricted to controlled commercial educational tourism with a limit on total numbers of around 750 tourists per year (Parks and Wildlife Service 2006). Activities are limited to landing at two localities (the Australian Station at Buckles Bay and Sandy Bay) and cruising in Zodiac boats offshore from a large King Penguin colony. Some infrastructure (duck-board and viewing platforms) is in place at the two landing localities. One such structure has recently been undermined by a landslip, in an area grazed by European Rabbits (*Oryctolagus cuniculus* (Linnaeus, 1758)).

South Georgia has the greatest level of tourism in the sub-Antarctic. Most activities are based around the old whaling stations, the British Antarctic Survey base and areas of scenic beauty and wildlife congregation. The island has the largest number of tourist landings (upward of 4000 per summer season) due to its proximity to South America and has a large number of other vessels such as fishing vessels visiting as well (Frenot *et al.* 2005) (see pl. 1A). Tourist activities range from exploring historic sites and coastal areas, to ice climbing and retracing Shackleton's epic west-east trek across the spine of the island.

Whereas tourism is very controlled on Macquarie Island with ranger supervision, many tourist activities on South Georgia are unsupervised. For larger or remote islands there is little information available on uncontrolled short-term visits by small vessels such as yachts. Sequential island-hopping by vessels poses a potential threat to island ecosystems through poor quarantine standards and non-compliance with permit conditions. Tourist ships often schedule visits to the Falkland Islands before they visit South Georgia. The practice of visiting warmer islands before colder ones provides pathways for potentially transferring propagules of both native and alien species southwards.

Contamination

Contamination on sub-Antarctic islands follows a similar pattern to those summarised in Hull & Bergstrom (2006) for the Antarctic. All lands are subjected to some degree of long-range airborne contaminants from remote sources such as PCBs; however, as sub-Antarctic islands are distant from inhabited continents, they will be, like Antarctica, at the lower end of the global contamination scale. Such contaminants are known generally to accumulate in top-order predators.

Waste and contaminants associated with local occupation both in the past (legacy wastes) and present are the main group of contaminants in the sub-Antarctic. Wastes and contaminants from onshore sealing and whaling activities during the "historical era" would have been substantial. On South Georgia summer populations of up to 2000 men processed thousands of whale carcases. There was domestic waste and sewage associated with the human population, as well as industrial waste and contaminants discharged onto land and into ocean and atmosphere. Residues have been found in inshore marine sediments and benthic invertebrates. Whale bones are still visible, scattered on land in the vicinity of former whaling stations (Headland 1984). Waste whale carcase debris probably supported larger populations of scavenging birds than at present.

Contaminants from the "modern era", the past 50 years, are better-documented. Oil spills, rubbish dumps and sewage effluent are the main point sources. Other point sources include emissions from the operation of incinerators at stations and huts; non-point source emissions include aerially dispersed contaminants from vehicles (Deprez *et al.* 1994, Poland *et al.* 2003, Hull & Bergstrom 2006).

Past and present oils spills have occurred on most sub-

Antarctic islands. Large oil spills have occurred either near or within station limits on both Macquarie Island and Île de la Possession. The spill at Île de la Possession in 1997 occurred from an underground pipe at the Alfred Faure station. An estimated 20 000 L of diesel fuel drained through the ground to re-emerge some 200 m down slope in an area containing both arid fellfield vegetation and an area of wet closed vegetation. The area affected was approximately 1200 m^2. After one year 45% of hydrocarbons had been degraded by indigenous bacteria in some areas. However Coulon & Delille (2006) noted that the success of bioremediation depended on the characteristics of both the contaminant and substrate.

On Macquarie Island a number of fuel spill contaminated sites are associated with the station, particularly around the fuel farm, powerhouses and diesel mechanics' workshop (Deprez *et al.* 1994). Rayner *et al.* (2007) investigated potential means to bioremediate three petroleum-hydrocarbon spills associated with the fuel farm and powerhouses. They noted that bioremediation of subpolar soils can be limited by low nutrients, low temperatures and excess water causing anaerobic conditions. Their experiments reported on the success of a "microbioventing" system, comprising many small air-injecting rods that successfully aerated a wide area of soil and increased natural biodegradation rates of indigenous bacteria.

Agriculture

Agricultural practices were commonplace in the early human histories of most sub-Antarctic islands. Sheep (*Ovis aries* Linnaeus, 1758) were introduced to most sub-Antarctic islands with early sealing or scientific expeditions together with hay for feed which inadvertently introduced a number of agricultural alien plant species. A population of around 3000 sheep can still be found on Île Longue (Îles Kergeulen) (Chapuis *et al.* 1994) and are a major protein food source for expeditioners. Sheep are rounded up by a shepherd and sheep dog during summer months and transported live by barge to the abattoir at Port aux Français. Bourzat & Monie (1977 in Frenot *et al.* in press) reported "pasture improvement" practices were tried on Île Longue and another small island with seeding of European pasture grasses (*Elymus repens* (L.) Gould, *Dactylis glomerata* Linnaeus, *Festuca ovina* Linnaeus, *F. arundinacea* Schreber, *Lolium perenne* Linnaeus, *Poa pratensis* Linnaeus and *Phleum pratense* Linnaeus) in the 1970s. These species have established successfully and outcompeted native species. An examination of sheep paddocks near sheep infrastructure in early 2004 yielded only three indigenous species from a total expected native biodiversity of up to 25 plant species (N.J.M. Gremmen pers. comm.). This represents a substantial loss of native biodiversity. Mouflon (*Ovis musimon* Pallas, 1762) are present on Île Haute and reindeer (*Rangifer tarandus* Linnaeus, 1758) on Grande Terre of Îles Kerguelen (Chapuis *et al.* 1994).

On South Georgia, sheep were also confined to a single island, Mutton Island, off Husvik, but none remain. Following three introductions from Norway, two distinct populations of reindeer are still present on South Georgia (Leader-Williams 1988, Anon 2005), the Busen and Royal Bay herds, formerly confined to relatively small areas by adjacent glaciers. As glaciers have retreated with recent climate change, the reindeer have gained access to a larger area (Lindsay 1973), and they now occupy the most extensive and species-rich vegetated areas on South Georgia. Their grazing has caused degradation of vegetated areas and erosion of bare areas (McIntosh & Walton 2000). The continuing glacial retreat provides potential access for reindeer into new areas, leading to probable further degradation of plant communities (Moen & MacAlister 1994). Partly to satisfy the intense scientific interest in the genetics of these isolated populations, and partly to facilitate establishment of a commercial reindeer herd in the Falklands, in 2001 and 2002 fawns were translocated from the South Georgia herds to the Falkland Islands where they have been successfully established (Pasteur & Walton 2006). To minimise further environmental damage, eradication of the Busen herd within five years is planned, with eradication of the Royal Bay herd to be considered subsequently (Pasteur & Walton 2006).

HOMOGENISATION OF BIOTA

The most serious impact of humans on sub-Antarctic islands concerns the global issue of homogenisation of biota and the impact resulting from alien species. This topic has recently been reviewed substantially in Frenot *et al.* (2005, in press) and Convey *et al.* (2006). The main messages from these studies is that alien species richness, to a large extent, correlates with island size, visitation rates by people and temperature, with colder islands less susceptible to invasion than warmer ones (Chown *et al.* 1998, 2005).

A total of 108 alien vascular plant species has been recorded from the sub-Antarctic (table 2). Île Pingouins (Îles Crozet) and McDonald Island are free of alien plants and Îles Kerguelen has the dubious distinction of having the highest record with 69 alien species. Most species are classified as "persistent" and may have little detrimental impact beyond their presence; however, some notable species are "invasive" resulting in loss of local biodiversity (Frenot *et al.* 2005, in press). Grasses and daisies are the most common type of alien species with the winter grass (*Poa annua* Linnaeus) being the most widespread in the region. Other notable species (most European in origin) include *Cerastium fontanum* Baumgarten, *Rumex acetosella* Linnaeus, *Stellaria media* (L.) Villars, *Sagina procumbens* (Linnaeus) and *Poa pratensis*.

Seventy-one taxa of alien invertebrates have been recorded across the sub-Antarctic region (table 2). The most common groups are flies, aphids, beetles, mites and Collembola (springtails). Alien vertebrates include fish, rodents, rabbits, cats (*Felis catus* Linnaeus, 1758), birds and as mentioned above sheep, mouflon and reindeer (tables 2 and 3).

TABLE 2
Total number of alien species recorded from sub-Antarctic islands

	South Georgia	Marion	Prince Edward	Crozet	Kerguelen	Heard	Macquarie
Vascular plants	33	13	3	59	69	1	3
Invertebrates	12	18	1	14	30	3	28
Vertebrates	3	1	0	4	12	0	6

From Frenot *et al.* (2005).

TABLE 3
Number and types of alien vertebrates established on sub-Antarctic islands

	South Georgia	Marion	Prince Edward	Crozet			Kerguelen	Heard and McDonald	Macquarie
				Possession	Est	Cochons			
Ships rat				+			+		+
Black rat	+								
Mice	+	+				+	+		+
Rabbits					+	+	+		+
Sheep							+		
Mouflon							+		
Reindeer	+						+		
Cat		×				+	+		×
Trout		×		+[1]			+[2]		
Salmonid fish							+		
Mallard									+
Starlings									+
Red polls									+
Weka									×
Total alien vertebrate species	3	1	0	3	1	3	12	0	6

+ species present, × species has died out or has been removed through eradication activities.
[1] Two species.
[2] Four species.
From Frenot *et al.* (2005).

The majority of alien invertebrates, plants and rodents were accidental introductions, but some alien species were purposely introduced for other reasons such as pasture improvement (as described above), as food in the case of rabbits, fish and the ungulates or as transport (horses on Macquarie Island and South Georgia; Headland 1984, Cumpston 1968, K. Kerry pers. comm.). The European rabbit flea was purposely introduced to Macquarie Island to carry the introduced Myxoma Virus to assist with rabbit control (Copson & Whinam 2001).

Some alien species have died out naturally such as trout on Marion Island (Cooper *et al.* 1992) and some transient alien plant species (Frenot *et al.* 2005). Some alien species have been actively removed through eradication processes, such as removal of founder populations of *Anthoxanthum odoratum* Linnaeus and *Rumex crispus* Linnaeus on Macquarie Island (Copson & Whinam 2001) and eradication of cats from Macquarie and Marion islands (Bester *et al.* 2000, Copson & Whinam 2001, Parks and Wildlife Service 2006).

Impacts of alien species include both direct and indirect impacts, including substantial loss of local biodiversity, changes to ecosystem processes and changes to ecosystem evolution. Some species are reaching "transformer status" (*sensu* Richardson *et al.* 2000). On Marion Island, two invasive plants species, *Sagina procumbens* and *Agrostis stolonifera* Linnaeus, are expanding their distributions and dominating various habitats, modifying both vegetation and associated fauna (Gremmen *et al.* 1998, Gremmen & Smith 1999).

Rabbits can be considered as a transformer species on both Grande Terre in Îles Kerguelen and Macquarie Island, as can reindeer on South Georgia where they have significantly altered ecosystems through grazing (Copson & Whinam 1998, Moen & MacAlister 1994, McIntosh & Walton 2000). Rabbits also possibly contributed to the extinction of the Macquarie Island parakeet and land rail which had co-existed with cats for 70 years before rabbit arrival (Taylor 1979). On Grand Terre large areas are dominated by *Poa annua* (alien) and *Acaena magellanica* (Lam.) Vahl (native) with other species having been selectively grazed. *Acaena magellanica* expands vegetatively in these areas, as even their inflorescences are grazed. On Macquarie Island, rabbits were controlled for a substantial period through an integrated pest management regime (Copson & Whinam 2001). Their numbers appear to have increased recently and a range of compounding factors have been suggested as the cause: the removal of feral cats, built-up resistance to Myxoma Virus used to reduce rabbit numbers annually, the stopping of use of Myxoma due to its unavailability, climate change resulting in increased rabbit winter survival. Coastal slope vegetation in particular is being removed through grazing, possibly contributing to soil erosion and landslips (Parks and Wildlife Service 2006, Springer 2006). Bergstrom *et al.* (2006) reported that rabbits may also be impacting on ecosystem evolution on the island through restricting the expansion of a recently colonised grass species, *Poa litorosa* Cheesman.

Sub-Antarctic island ecosystems have evolved in isolation and such ecosystems lack resilience to alien species invasions. Many ecosystems have missing functional groups that can be easily filled by alien species (Bergstrom & Chown 1999). This has occurred on both South Georgia and Îles Kerguelen where carnivorous beetles have been introduced (see Convey *et al.* 2006 for full discussion) and these species are preying on native populations of invertebrates that became established within sub-Antarctic ecosystems without predator pressure.

HUMAN-INFLUENCED CLIMATE CHANGE

The final human impact to discuss here is that of current human-mediated climate change. Convey (2006) describes climate change in terms of impacting on four key parameters: temperature, free water availability, UV-B radiation and carbon dioxide levels. Changes in temperature and water availability have been noted on some islands; UV-B and CO_2 levels have not been extensively studied in the sub-Antarctic. Increases in temperatures have been recorded from many sub-Antarctic islands (Adamson *et al.* 1988, Smith & Steenkamp 1990, Frenot *et al.* 1997, Tweedie & Bergstrom 2000, Smith 2002, Le Roux & McGeoch, in press). There have been decreases in precipitation at both Marion Island and Îles Kerguelen since the early 1950s (Smith & Steenkamp 1990, Frenot *et al.*1997, Smith 2002, Chapuis *et al.* 2004, Le Roux & McGeoch in press).

Impacts of these changes include changes in local vegetation types (Smith *et al.* 2001) and animal-plant interactions (Chown & Smith 1993). On Macquarie Island the distribution of *Sphagnum* appeared to be expanding through the 1980s. The reduction in area of patches between 1992 and 2004 is interpreted as due to a period of desiccation in 1999–2000 (Whinam & Copson 2006). On all sub-Antarctic islands with extant ice caps, warming has resulted in glacial retreat and greater land exposure (see Frenot *et al.* 1997, Gordon & Timmis 1992, Sumner *et al.* 2004, Ruddell 2006). Recolonisation of these glacial forelands by both indigenous and alien species has been documented in detail (Scott 1990, Frenot *et al.* 1997, Frenot *et al.* 1998, Scott & Bergstrom 2006). There is also some evidence of *Acaena magellanica* overgrowing *Azorella selago* Hook.f. at lower altitudes (Scott & Bergstrom 2006).

On Heard Island the distribution of *Poa annua* is expanding at an alarming rate (Scott & Kirkpatrick 2005). Whether this is related to climate warming is as yet unclear. Expansion of alien species and increased opportunity for alien species establishment or phase change (from persistent to invasive, from invasive to transformer species) is predicted to be one of the major changes on sub-Antarctic islands associated with climate change (Selkirk 1992, Convey *et al.* 2006).

CONCLUSIONS AND PATHS FORWARD

There are only a few sub-Antarctic island groups on the planet: six to eight, depending on how one classifies their ecosystems. This means that sub-Antarctic islands are some of the rarest ecosystems on the planet, making them very significant. Some have been more heavily impacted by human activities than others. Those which have been least impacted, McDonald Island, Prince Edward Island, some of the outer islands of Îles Kerguelen and Heard Island, are of particular significance and require greater vigilance in their management.

The impact of past human activities such as sealing and whaling continues to the present, with species recovery still occurring and the infrastructure from such activities breaking down and polluting their local environments. Some scientific infrastructure, such as the abandoned Atlas Cove station at Heard Island, is still polluting the local environment despite many attempts at clean-up. The constant harsh sub-Antarctic environment applies significant stressors to human structures and any placement of new infrastructure must be accompanied by a plan for its removal before it is destroyed by the environment.

By far the greatest threat to sub-Antarctic ecosystems is the impact of alien species and the confounding effect of climate change to conditions which may favour non-native species. Some alien species have been eradicated, such as cats on Marion and Macquarie islands. Vertebrates by and large can be removed if sufficient resources are made available as long as an integrated pest management system is put in place. Most sub-Antarctic islands have persistent alien plant species. Removal of alien plants at this stage is desirable but to eradicate extensive populations of invasive plant species and any alien invertebrates is very difficult if not impossible. Such invasions inevitably cause permanent change to the ecosystem.

Chown *et al.* (2005) reported that alien plant and insect species on Southern Ocean islands (including the sub-Antarctic islands) covaried with human visitation rates. Whinam *et al.* (2005) began the study of examining pathways of alien propagules into the sub-Antarctic, identifying cargo, food and expeditioners' clothing, gear and equipment as all potential means of transport to these remote islands. They also demonstrated the success of adaptive management practices to prevent propagule transport. Australia and South Africa now have strong quarantine management practices in place. Whinam *et al.* (2005) also highlighted the difficulty in applying such quarantine practices to tourism operations. In particular the large size and unregulated nature of tourist operations make South Georgia stand out as now under serious threat.

Clearly humans and their activities have impacted substantially on sub-Antarctic terrestrial ecosystems in the past and in continue to do so in the present. By projection it must be expected that both direct and indirect human impact will continue into the future. The overwhelming message is that there is need for prevention as well as cure. It is appropriate to plan all future human activity in the rare sub-Antarctic ecosystems in ways that will minimise further impact.

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HISTORY, EXPLORATION, SETTLEMENT AND PAST USE OF THE SUB-ANTARCTIC

by Rodney Russ

(with six plates)

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Human impacts on the sub-Antarctic islands stem from sealing and whaling, alien species of plants and animals resulting from human incursions (both temporary and permanent), shipwrecks, settlements and weather stations arising from the Second World War, collecting by scientific expeditions, scientific stations and tourism. Many of these factors remain as important issues for the health and maintenance of the sub-Antarctic.

Key Words: human-impact, sub-Antarctic, sealing, whaling, alien species, tourism, weather stations, scientific incursions, shipwrecks.

INTRODUCTION

The definition of the sub-Antarctic islands used here is that of Clark & Dingwall (1985) with one exception. The Falkland Islands are excluded since their extensive development makes it difficult to include them in a general discussion. Heard Island and the McDonald Islands are considered as one entity and Marion and Prince Edward islands as another. This has resulted in 19 islands or island groups.

This paper considers the broad topic of human impact, a big task considering that entire books have been written about individual islands. Comments on human impacts are restricted to the post-European discovery period, but recent evidence from Auckland and Snares islands suggest the possibility of pre-European settlement and activity there (Anderson 2005).

Some claim oral traditions of early Polynesian voyaging to other New Zealand sub-Antarctic islands, but there is no record of any of these traditions in the works of any of the early New Zealand ethnographers — such as Herries, Beattie, Peter Buck or Elston Best (Buck 1954).

European discovery of these islands spans 327 years from 1505 (Gough Island) to 1833 (Heard and McDonald islands). This period corresponded with a significant increase in human activity in the Southern Ocean, much in the early years centred on the search for *Terra Australis Incognito*, the fabled southern land that was supposedly balancing the globe. On more than one occasion these sub-Antarctic islands were thought to be part of that great continent (Headland 1984). Twelve of the 19 islands were discovered in the last 61 years of that period (1772–1833).

If there is one common thread or theme that unites all these islands it was, or is, sealing. Sealing first began in the Southern Hemisphere in the Falkland Islands much earlier in about 1766 (Headland 1984) spreading quickly to the islands off the west coast of South America and from there to the islands being considered. None of the islands or island groups under consideration escaped the impact of sealers.

Three species of fur seal (Antarctic Fur Seal, *Arctocephalus gazelle* (Peters, 1875), Sub-Antarctic Fur Seal, *A. tropicalis* (J.E. Gray, 1872) and New Zealand Fur Seal, *A. forsteri* (Lesson, 1828)) were hunted. Their skins were fetching high prices in China because at this time it was only the Cantonese that knew the furriers' craft of removing the coarse guard from seal skins to leave the soft inner fur (Busch 1985). The demand for seal skins intensified the search of new rookeries and new islands. Campbell, Macquarie, the South Orkney and South Shetland islands were all discovered by sealers.

The impact of sealing on the seal population was immediate and obvious; entire populations were almost exterminated, killings were indiscriminate — young, old, male and female were killed: The rivalry between gangs meant there was no hope of any conservation measures; any animals left behind by one gang would be slaughtered by the next, or possibly poached by a neighbouring gang. It was a scorched earth or scorched rookery policy (Grady 1986).

Hookers Sea Lions (*Phocarctos hookeri* (Grey, 1844)) were also targeted, although this industry was restricted to Auckland and Campbell islands and the Snares where the animals breed. Sealers were landed on all the islands to be left there for weeks, sometime months, and there are numerous accounts of gangs being marooned for years. Many of them died on the islands either from injury or illness (Grady 1986).

In addition to the basic rations, animals were sometimes landed to provide extra food. Pigs (*Sus scrofa* Linnaeus, 1758) were a popular choice, as they appear to have been easy to keep alive on board the ship. European rabbits (*Oryctolagus cuniculus* (Linnaeus, 1758)) and goats (*Capra hircus* Linnaeus, 1758) were also landed. Pigs and rabbits provided multiple offspring; goats would have provided both meat and milk. Some of these populations survived and established viable populations (Ross 1847). Others soon died out because of the severe climate or through having eaten out all suitable food.

Those populations of introduced animals that did establish had a major impact on the island ecosystems (Micol & Jouventin 2002). For these islands, which had evolved in the absence of browsing animals there was no time to adapt or to change, the impact was immediate (Hooker 1847). Time has lost much of the detail, but there is strong evidence that ships' cats (*Felis catus* Linnaeus, 1758) were probably taken ashore as pets for sealers, as cats were reported ashore soon after discovery of a number of these islands (Johnstone 1985). Whenever they arrived, either with the first or with later sealing gangs, is academic although they certainly had a profound impact, especially on the bird life (Fraser 1986).

Rats (*Rattus rattus* Linnaeus, 1758) and mice (*Mus musculus* Linnaeus, 1758) had a similar effect. The arrival of these onto some of the islands can be dated with, or soon after, the arrival of sealers (Cumpston 1968). For other islands it is not so clear. Some introductions may have resulted from shipwrecks; others may have come with stores unloaded for sealers. However they arrived, based on observations made in 1964 when rats got ashore on Big South Cape Island off the west coast of Stewart Island, the destruction would have been overwhelming (Bell 1978). The availability of food on these islands would have meant that numbers mushroomed and entire species were wiped out. A parakeet and a flightless rail became extinct on Macquarie Island, and sub-fossil bones have now confirmed that a parakeet species that was never reported or recorded was lost from Campbell Island (Holdaway 2005). A flightless duck and storm petrel were lost from Amsterdam Island (Shirihai 2002). Further work from sub-fossil bones from other islands will undoubtedly reveal other extinctions.

The impact from these "first settlers" was not limited to their deliberate or accidental introductions. The sealers supplemented their rations with wildlife from the islands. Those species taken for food included various species of albatross (Cumpston 1968). Eggs, young and adults were taken. Penguin eggs were collected in their thousands (Cumpston 1968). Waterfowl and other species were shot both for food and undoubtedly for sport.

Fur seals became scarce and harder to find, and sealers turned their attention to "oiling" or the extraction of oil from Southern Elephant Seals (*Mirounga leonine* (Linnaeus, 1758)). Because of limitations on the processing of oil, this industry lasted or persisted longer than the taking of fur seals (Cumpston 1968). The animals were killed, the blubber cut off and transported to the trypots, then rendered down before storing the oil in barrels. It is claimed that a good "fur sealer" could kill and skin 60 animals an hour whereas the processing of elephant seals' blubber severely limited the number of animals that could be killed at any one time (Cumpston 1968).

Elephant Seal "oiling" was also an industry that required a certain amount of infrastructure and a reasonable amount of capital so relied on individuals or companies to invest a significant amount of money.

As Elephant Seal numbers declined, "oiling" companies looked for other ways to utilise their investment in plant and equipment. On a number of the islands penguins, mainly King Penguins (*Aptenodytes patagonicus* Miller, 1778) but also Royal Penguins (*Eudyptes schlegeli* Finsch, 1876) from Macquarie Island, were processed (pl. 1). Penguin oil was in demand but it was much harder in the very primitive conditions to produce a premium product. Even small amounts of blood mixed with oil meant the product fermented and was unusable (Cumpston 1968).

Whales, which often came close inshore at some islands during migration, were also targeted for their oil (pls 2, 3). Where Southern Right Whales (*Eubalaena australis* (Desmoulins, 1822)) bred in the sheltered harbours, whalers established themselves on shore and hunted using longboats (Grady 1986). This form of whaling was later referred to as "Bay Whaling". Where breeding animals were targeted entire populations were wiped out quickly. As the resources "dried up" or ran out, these "semi-permanent" settlers left the islands in search of their next El Dorado (Grady 1986).

The islands would never be the same; not one of them was spared the impact from the sealing and oiling era. Those at higher latitude like Heard, Bouvetøya, South Orkneys, South Shetlands and South Sandwich islands fared better than others on account of their extreme weather. Rats, mice and other introduced mammals could not survive in these harsh climates.

After the nomadic and opportunistic sealers and oilers came what are here termed the "Hopeful Immigrants". Six of these islands or island groups have had permanent settlement at some stage since their discovery. Today, Tristan da Cunha is the only one with a permanent population — about 80 families live on the island. St Paul Island had two periods of permanent occupation from 1843 to 1932. At the peak there were approximately 150 people living on the island employed in the fishing industry (Clark & Dingwall 1985).

The Auckland Islands were settled by two groups of people. Maoris who had migrated from the North Island of New Zealand to the Chatham Islands in 1830s then migrated on to the Auckland Islands in 1845; they were eking out a subsistence living when immigrants of the Enderby Settlement arrived direct from England to establish a colony around farming, whaling and ship repair (Fotheringham 1995). Sadly for the immigrants, the soil and weather were unsuitable for farming, the "Bay Whalers" had killed out the whales, and there was virtually no ship-based whaling left in the Southern Ocean — consequently there were no ships to repair. The Enderby Settlement folded after just three years; many of the Maoris who had become integrated into the colony left at the same time; others chose to remain. The last of these departed in 1855 (Dingwall *et al.* 1999).

Campbell Island was advertised as a pastoral run in 1895 and it was stocked with sheep and cattle. The lease changed hands and stock numbers were increased. At its peak the island carried 4,000 head of stock. Isolation, falling wool prices and increased shipping costs in the 1930s meant it was no longer economical and it was abandoned in 1932 (Kerr 1978).

When Kergulen Island was finally annexed by the French in 1893 a 50-year sealing/whaling and farming licence was issued. This station operated from 1908 to 1925. Stock were introduced to this island and neighbouring Amsterdam Island but were abandoned on Amsterdam as it proved too difficult to work (Clark & Dingwall 1985).

South Georgia Island was first settled in 1904 when a permanent whaling station was established at Grytviken (pl. 4). Another five whaling stations were to be built on the island. Leith Harbour Station was the last to close — in December 1965 (Headland 1984).

Permanent settlement of these islands only compounded the impact that had begun with the sealers. Stock, including cattle, sheep, reindeer and rabbits were introduced. The husbandry of this stock meant managing the environment. In many instances fires were deliberately lit to modify or attempt to improve the pasture (Kerr & Judd 1978). A number of introduced plants now occur on many of these islands (Clark & Dingwall 1985). It is impossible to list them all here but three (*Poa annua* L., *Stellaria media* (L.) Vill. (or chickweed) and *Sonchus oleraceus* L. (or soft thistle)) are widespread. How they arrived, or when, at individual islands can only be speculated — but as soils became disturbed seeds from these and other species became established.

Forest once covered 27% of Amsterdam Island but large fires, some of them lasting months, reduced this to just 5 % (Shirihai 2002). Fires killed ground-nesting birds especially

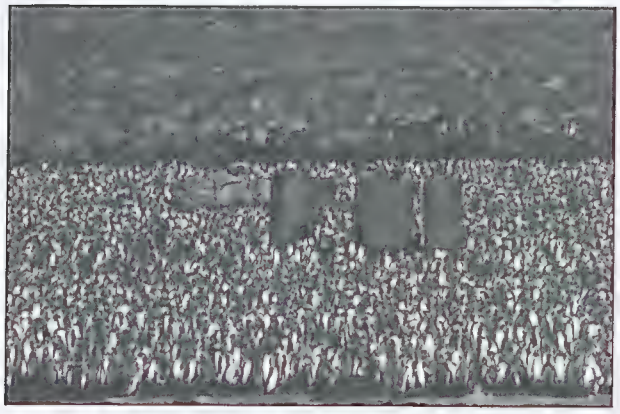

PLATE 1
Digesters, Lusitania Bay, Macquarie Island

PLATE 2
Whaling Station, Port Jeanne d'Arc, Grand Terre, Îsles Kerguelen

PLATE 3
Whaling Station, Port Jeanne d'Arc, Grand Terre, Îsles Kerguelen

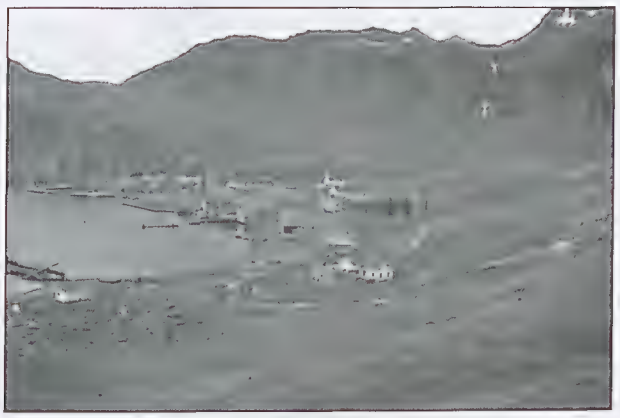

PLATE 4
Grytviken Whaling Station, South Georgia

PLATE 5
Stove, Homestead Cove, Campbell Island

PLATE 6
Plough, Homestead Cove, Campbell Island

albatrosses and giant petrels. Fire also removed important ground cover, allowing skuas and other predators access to seabird burrows — increasing predation on those species that had survived the arrival of the cats and rats (Clark & Dingwall 1985).

Cultivated grasses were introduced and stock was controlled by fencing. This often resulted in overgrazing of some areas and trampling of fragile areas where seabirds had previously nested (Dingwall & Gregory 2004). Settlers brought domestic pets, including dogs (*Canis familiaris* Linnaeus, 1878) and cats, and descendants of these would have added to the gene pool of those abandoned earlier. Rats and mice often accompanied these settlers either on ships or in their equipment. Where the species already existed on these islands they added to the existing gene pool, or otherwise established new populations (Taylor 1968).

In most instances these permanent settlements did not last long and were abandoned, South Georgia being the exception. Often the last settlers to leave simply shut the door and walked away, leaving behind vast amounts of machinery and equipment (Headland 1984) (pls 5, 6). In contrast, the settlers at the Auckland Islands took everything with them — it was sold in Sydney to try and pay off some of the debts of the settlement. On all the islands, the bulk of what was left behind by these settlers will simply rust or rot away — or occasionally be restored as a reminder of a bygone era.

These "Hopeful Immigrants" weren't the last of the settlers. Another five groups have impacted and continue to impact islands in some way or another.

More than 50 ships were wrecked on these islands. Some of the survivors spent months or even years on the islands before being rescued, many of them surviving on what food they could catch. Penguin eggs, albatross and albatross eggs were taken. Governments placed castaway depots on some of these islands, regularly re-supplied them with food, and in many instances liberated stock and planted seeds as food for potential castaways (Fraser 1986).

The Second World War highlighted the strategic importance of these isolated islands. Weather stations were established on some; others were occupied to prevent them falling into the hands of the enemy and coast watchers were placed on others. Wherever permanent populations were established there was an impact (McEwen 2006).

Numerous scientific expeditions have called at all these islands at various times. Some visits have lasted a few hours, others months. Some of the earliest expeditions predate sealing (Cumpston 1968). The impacts of these expeditions cannot be ignored but they are harder to measure. However, there was a period when "collecting" museum specimens was acceptable and profitable. Significant sums of money were paid for the right species. Collecting probably contributed to the extinction of the Auckland Island Merganser (Williams & Weller 1974). Today the impact of scientific expeditions may not be as dramatic as collecting a species to extinction. It might be a subtle transfer of minute organisms or seeds from one island to another or from the port of departure.

Of the 19 islands or island groups under consideration excluding Tristan da Cunha, nine have permanent scientific stations. The largest is the French base at Kerguelen Island with a summer population of around 120 people. All the others with the exception of the Bounties have some form of scientific camp or hut which is visited periodically, mostly on an annual basis.

Tourism is not a new phenomenon in the sub-Antarctic islands. There has always been a strong interest in the islands. Because it is hard to define when a person is a tourist and when they are not, it is impossible to say when tourism started, or who started it. The New Zealand government steamer was carrying tourists as early as the 1890s (Richardson 1890). However, the modern era is generally accepted as starting in the late 1960s with Lars-Eric Lindblad (Fraser 1986). As almost all sub-Antarctic tourism has been ship-based it is difficult to quantify its impact apart from noting that it would certainly have had some impact.

None of the sub-Antarctic islands or the island groups considered here has had continuous human occupation from discovery to the present day. All, without exception, show some impacts of human presence. Only now is the story of their discovery and of the impact of people upon these islands being researched and told.

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TOURISM IN POLAR REGIONS AND THE SUB-ANTARCTIC ISLANDS

by Denise Landau

(with one text-figure and one table)

Landau, D. 2007 (23:xi): Tourism in polar regions and the sub-Antarctic islands. *Papers and Proceedings of the Royal Society of Tasmania* 141(1): 173–180. ISSN 0080-4703. International Association of Antarctica Tour Operators (IAATO), PO Box 2178, Basalt, CO 81621, USA.

Tourism in the Antarctic is coordinated by the International Association of Antarctica Tour Operators (IAATO) which has regular meetings with the Antarctic Treaty parties. It keeps full records of visitation to the Antarctic and develops guidelines for the conduct of tourist activities so that the needs of tourists, the science community and the Antarctic environment are cared for. The sub-Antarctic has not been a major tourist destination or regulatory focus for IAATO as most sub-Antarctic islands are under national jurisdiction; thus visits to this region are either on the way to or from the Antarctic. Considerable visitation to the sub-Antarctic is conducted by non-IAATO operators. Statistics equivalent to those collected for the Antarctic are not available through IAATO; however, many of the IAATO guidelines are relevant to sub-Antarctic activities. This paper outlines IAATO's history, its guidelines and issues for the future.

Key Words: tourism, Antarctic, sub-Antarctic, IAATO, impacts.

INTRODUCTION

Without the vision of Lars-Eric Lindblad, a tourism pioneer from Sweden, tourism in the sub-Antarctic islands and the Antarctic might not have begun when it did. Lindblad saw a market for tourism that coupled adventure travel with education as a primary theme, as well as a focus on the preservation of the environment, particularly its wildlife. As a result, the 100-passenger vessel *Lindblad Explorer* was built for its first cruise to Antarctica in 1970. Tourism to the sub-Antarctic and the Antarctic has evolved without any significant environmental incidents for nearly 40 years. This paper reviews the history and evolution of tourism to the sub-Antarctic and Antarctic as a contribution to the understanding of the importance to the sub-Antarctic of a new and growing industry.

As awareness of the polar regions grew, the industry expanded and more vessels and operators appeared in the Antarctic. The sphere of operation included not only relatively short cruises from gateway ports in South America, but also cruises in the Ross Sea and East Antarctica south of Australia and New Zealand. Vistas of the Transantarctic Mountains and historic huts on Ross Island and Cape Adare were, and still are, the primary features on itineraries, but added attractions are Macquarie Island and the sub-Antarctic islands of New Zealand, all of which offer extensive wildlife experiences. The advent of Russian icebreakers with onboard helicopters in the 1992–1993 austral summer added to the ability to access new island groups in the Indian Ocean (Îles Crozet, Îles Kerguelen, Heard Island), plus coastal areas of Antarctica. Here an icebreaker is needed to visit remote areas such as Emperor Penguin (*Aptenodytes forsteri* Gray, 1844) colonies, research stations and Taylor Valley, one of the dry valleys in southern Victoria Land that would otherwise be inaccessible. An added achievement was the first-ever circumnavigation of Antarctica by a tourist vessel — the Russian icebreaker *Kapitan Khlebnikov* — in the 1996–1997 season. Visits to sub-Antarctic islands remain highlights of itineraries of the tour ships using the gateway ports in Australia and New Zealand. A fly-over form of tourism using Boeing 747-400 aircraft is a popular attraction for tourists, and enables them to see coastal features south of Australia and New Zealand and in the Ross Sea, using Australia as a base for the fly-overs. No landings are made in these "scenic-only" flights. These flights occasionally allow a view of sub-Antarctic islands such as Macquarie Island and the Balleny Islands.

Ship-borne tourism added a new dimension to Antarctic activity in the early 1990s with the introduction of a variety of tour vessels — such as ice-strengthened vessels and a powerful icebreaker — capable of travelling in ice-filled waters. As the industry grew, appropriate management strategies evolved in response to the fragile environment of Antarctica and the need to protect it. The history of IAATO and its development, particularly the evolution of management strategies in response to perceived needs, was summarised by Splettstoesser & Folks (1994), Splettstoesser (2000) and Landau & Splettstoesser (2007).

The need for a coalition of tour companies became apparent in the early 1990s; the seven operators in Antarctica united in 1991 to form the International Association of Antarctica Tour Operators (IAATO). Competition was replaced by cooperation, and the pool of knowledge and collective experience of those founder members has become the secret of its success. As membership increased with new operators, a single voice was needed to speak for the industry, as a participant at the Antarctic Treaty Consultative Meetings (ATCMs) and other important venues where tourism issues have become major subjects of discussion. The current membership of 97 (2007), represents activities in ship-borne tourism together with one operator offering adventure tourism in the interior of Antarctica. Members come from 15 countries plus the Falkland Islands/Islas Malvinas, and comprise a variety of organisations and operators, including ship owners, land-based and fly/cruise operations, ship agents, suppliers, conservation groups, governments and specialised adventure operators. From initial small beginnings, consisting of small expedition ships or small boat operations for shore visits and cruises, there are presently some 50 vessels, including small yachts, ice-strengthened ships, large ships carrying as many as several thousand passengers (but without landings), fly-overs for scenic viewing without landings, and ship-based adventure tourism. This last type of tourism includes skiing, camping,

mountaineering, kayaking, small boat cruising (Zodiac, Naiad, Polar Cirkle), helicopter operations and SCUBA diving. Specialised guidelines have been compiled for these activities and others to ensure that all activities will have no more than a minor or transitory impact on the Antarctic environment (IAATO 2007a). Visits to scientific stations are a relatively common feature on itineraries, with rigid guidelines which tour operators must follow in order to conduct orderly visits without interfering with science activities.

Many of these activities also relate to the Arctic and other parts of the world; when tour businesses cannot operate in Antarctica (from November to March) they are conducting cruises and expeditions in other parts of the globe. Statistics from Antarctic itineraries are monitored through a system of post-visit reports, and the resulting statistics are maintained in a database that includes numbers of passengers and crew, and nationalities of all visitors. These data become part of the IAATO reporting system presented as Information Papers at Antarctic Treaty Consultative Meetings. These can be viewed on the IAATO website (IAATO 2007a) by following the link labelled "Information Papers". A comparable system for the sub-Antarctic islands is discussed below, and the Falkland Islands/Islas Malvinas will be included in the reporting system and database soon.

The types of guidelines mentioned are included on the IAATO website (IAATO 2007a). Some are posted on the open pages although the majority are on the members-only website. They have also been applied to the itineraries of operators that include visits to sub-Antarctic islands to view wildlife and undertake station visits (e.g., Macquarie, Kerguelen, Crozet, South Georgia). Frequency of visits to islands and other sites listed here are recorded using information tabulated from post-visit reports from the Antarctic Treaty area, and also from operators' printed itineraries. At the eighteenth Annual General Meeting of IAATO held in Hobart, Tasmania, in 2007, IAATO members agreed that their basic operating procedures, as specified in IAATO bylaws and guidelines, would also be applied north of latitude 60°S to the boundary of the Antarctic Convergence, or Polar Front, in order to include the area of jurisdiction of The Conservation of Marine Living Resources (CCAMLR), thus strengthening efforts to protect the Antarctic environment. This northward boundary would thus include South Georgia, Îles Kerguelen and Heard Island.

GLOBAL RANGE OF SUB-ANTARCTIC TOURISM

The popular attractions provided by ship-borne tourism in the Antarctic Peninsula and Ross Sea area, offshore island groups in the Treaty area and many sub-Antarctic islands comprise an important aspect of the range of tour operators' activities, many of them under Treaty party jurisdiction. Commonly visited islands in the Antarctic Treaty area include the South Shetland Islands, which take in Elephant Island and Deception Island. Less frequently visited islands in the Treaty area include the South Orkney Islands, Balleny Islands, Scott Island and Peter I Island. Islands outside the Treaty area visited occasionally or frequently include Macquarie Island (Australia), Campbell Island (New Zealand), Enderby Island (New Zealand), Auckland Islands (New Zealand) and Snares Islands (New Zealand) (the latter involving small boat cruising only, no landings). Others that have been visited in the past include Chatham Island (New Zealand) Heard Island (Australia), Îles Kerguelen (France), Amsterdam Island (France), Saint Paul Island (France), Îles Crozet (France) South Sandwich Islands (United Kingdom), Tristan da Cunha (United Kingdom), Nightingale Island (United Kingdom), Bouvetøya (Norway) and Islas Diego Ramirez (Chile) One of the more frequently visited island groups is the Falkland Islands/Islas Malvinas, partly because it is occasionally a changeover location for passengers and the start of following itineraries.

TOURISM TRENDS AND STATISTICS

The numbers of tourists annually have increased gradually, with some 37 500 in the 2006–2007 season visiting Antarctica, of which approximately 25 000 landed on the continent, and 8000 either over-flew or cruised only. In the 2005–2006 season, for comparison, somewhat more landed in Antarctica, however, and some 6000 visited the remote sub-Antarctic islands in about 40 vessels. Figure 1 summarises the annual figures and trends in tourist numbers from 1992–1993 through 2006–2007 (approx. 29 500, for those who landed only), as well as projections made for 2007–2008. Estimates of the total number of tourists for 2007–2008, including landings and other categories, total some 44 000 (see also Landau & Splettstoesser 2005, Table 12.1). The total figures for each season can be broken down into the type of tourism conducted. For example, not all tourists step ashore on land, many are included in over-flights without landings, and others are on cruise-only itineraries without landings (table 1).

IAATO has not maintained statistics on visits to sub-Antarctic islands to date, but IAATO's present organisation and infrastructure could readily be modified to incorporate those areas into the database. It is presently not a requirement of Treaty parties to maintain these data, but parties that govern several islands under jurisdiction maintain statistics for tour visits.

Tourist visits to sub-Antarctic islands

Figures for numbers of tourists visiting sub-Antarctic islands are not conveniently summarised, perhaps because of the lack of a central coordinating organisation such as IAATO. Some data from recently published literature are as follows.

South Georgia

Modern-day tourism began in South Georgia in 1970, with regular visits in the 1970s and 1980s. Poncet & Crosbie (2005) provided information on early tourism to the island, culminating in more than 40 ships each season carrying some 3500 passengers. Snyder & Stonehouse (2007) tabulated tourist visits for the period 1991–2006, showing 11 ship visits in 1991–1992 to as many as 49 ships (plus 28 yachts) in 2005–2006, for a total of 5436 passengers in that season, not counting staff and crew.

New Zealand's southern islands

These islands are relatively convenient to visit because they are often on itineraries for tour vessels that visit Antarctica. Dedicated tourism visits began in 1968, and during the following 20 years some 1300 tourists are estimated to have visited, and in the five years following that a further

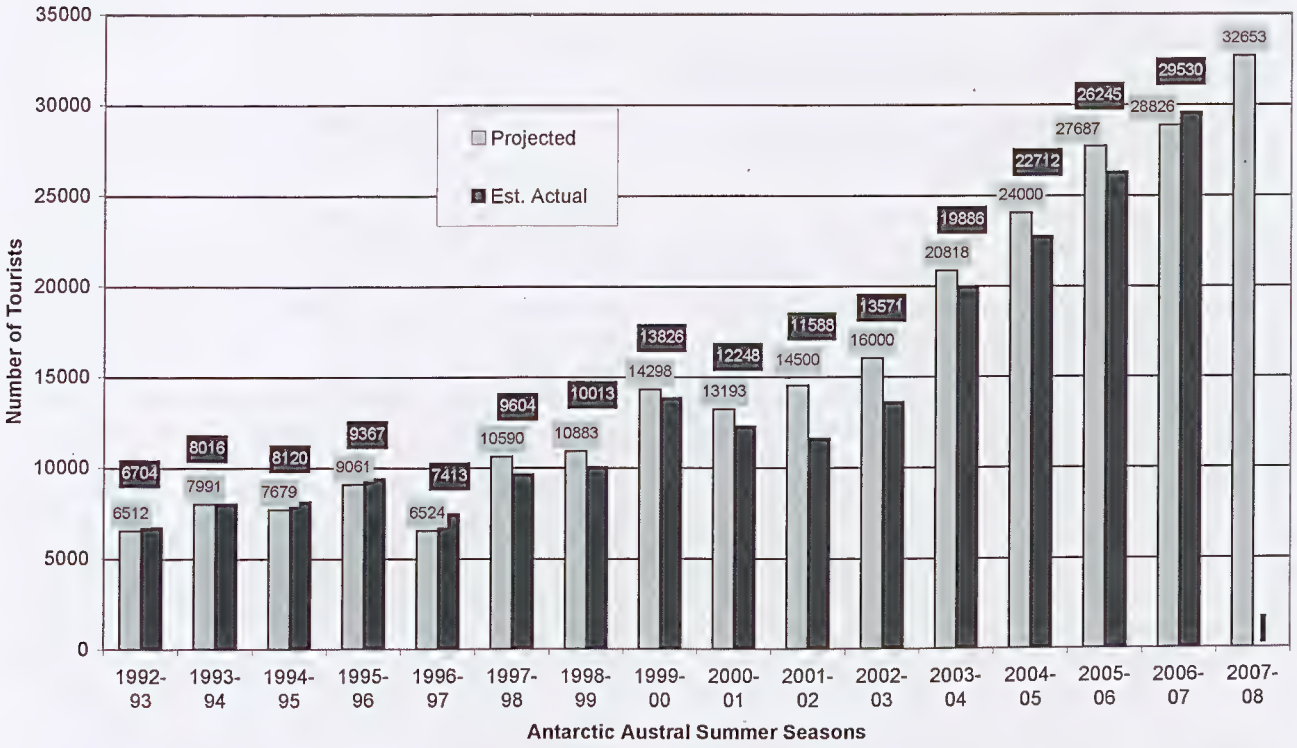

FIG. 1 — 1992–2007 Antarctic tourist trends: landed (includes ship and land-based passenger numbers. 1997–98 onwards includes some commercial yacht activity).

TABLE 1
Total visitor passenger estimates for the 2006–2007 season[1]

Type of tourism	Numbers
Seaborne traditional tourism (with landings)	28 448
Seaborne tourism cruise-only (no landing)	6930
Air/cruise	174
Air/land-based "traditional" tourism	908
Over-flights (no landing)	1046
Total	37 506

[1] From IAATO (2007).

1550 tourists landed (Tracey 2007). Due to high demand in 1991–2001 a seasonal limit on visitor numbers was set at 600.

Macquarie Island

The first tourist visit to the island was in 1971, and subsequent visits, occurring annually from 1992–2003, are a part of itineraries for Antarctica-bound vessels, which may include New Zealand's southern islands. Tourist landings take place at two sites, with small-boat cruising at another. Present guidelines limit numbers to 750 visitors each season, although in no season have they exceeded 560 (Tracey 2007).

Heard Island

Only three visits by tourist ships are recorded (1992, 1997 and 2002) and five small private expeditions (Tracey 2007). Difficulty of access and stormy weather are deterrents to tourism, although in 1992 one helicopter flight was made to a shore-based research group to deliver mail and provisions, and later in that season, a landing was made by Zodiac at another location for the same purpose. In the first instance, three passengers got ashore, and in the second, one passenger plus ship staff. In 1997, helicopters were used to transport passengers ashore at Atlas Cove and most, if not all, of the ship's 90–100 passengers got ashore (1992 and 1997 information: J. Splettstoesser pers. comm. 2007). Since 1997 ships have visited Heard Island but IAATO has not kept specific numbers of visits.

Tristan da Cunha group

Tour ships have visited Tristan da Cunha almost annually since the 1970s, landing on the unprotected beach. But visits have taken place more frequently since a breakwater was constructed in 1967. Nearby Nightingale Island also receives visitors, escorted by Tristan inhabitants.

Îles Crozet and Îles Kerguelen

With the introduction of Russian icebreakers for use in Antarctic tourism in the 1992–1993 season, several sub-Antarctic islands have been visited, some annually. In the 1992–1993 austral summer, Îles Crozet (once) and Îles Kerguelen (twice) were visited, each time with about 80–90 passengers. The French stations were visited each time. They were visited again in the 1997–1998 summer, with about 95 passengers on each visit. Subsequent visits have taken place since 1998 but IAATO has not collected statistics.

St Paul Island and Amsterdam Island

Both islands were visited in January 1993, St Paul by about 80 passengers, and Amsterdam by ship staff only on a single helicopter flight to the French station under foggy conditions that nearly aborted the visit (J. Splettstoesser pers. comm. 2007).

South Sandwich Islands

This island group was visited nearly annually beginning in the early 1990s by a Russian icebreaker, and in later years by small expedition vessels. Two cruises took place each summer and within five or six seasons, five islands out of the 11 main islands were visited by tourists, either by Zodiac landings or helicopter, or both. Approximately 80–90 passengers were on each icebreaker cruise, although not all got ashore because of threatening sea conditions (J. Splettstoesser pers. comm 2007).

PROJECTIONS FOR ANTARCTIC TOURISM

Projections for tourism in Antarctica show a gradual increase in numbers of visitors. Specialised management techniques and strategies are required by specialised forms of tourism, such as adventure tourism, to maintain environmentally-safe activities. The growth in numbers can be viewed as a trend but these increased numbers are not necessarily related to environmental impacts. These trends can be used to increase our understanding of tourism in general, as well as the management strategies and protective mechanisms required. Since organised tourism began in Antarctica in the 1970s, there has been no significant evidence of the cumulative impact on the environment of more than a minor or transitory nature. This level of impact has been determined from observations of experienced expedition staff, as well as government and other observers on cruises. These data are held by IAATO. The advantage of the tourist ship as the hotel is seen as a major factor in this regard.

Statistics collected by IAATO for tourism include the following: numbers of passengers; numbers of crew; nationalities of the above individuals; numbers and names of vessels and their registrations; size and type of vessels and aircraft; numbers of land-based tourists (not operators); and activities such as skiing, hiking, climbing, camping, SCUBA diving and small boat (Zodiac, Naiad, Polar Cirkle) cruising, landings, kayaking and hovercraft (IAATO 2007a).

With the increasing numbers of tourists the numbers of tour operators and ships has increased. The sizes and types of vessels vary depending on the operator, and include both ice-strengthened and non-ice-strengthened ships, icebreakers, yachts, and passenger capacities of about 40–50 for smaller vessels to as many as 3000 for one of the larger ones, the latter conducting cruise-only operations. Because of the restriction on landings, larger ships agree not to land passengers in accordance with IAATO bylaws. As the number of vessels and tourists has increased, so has the industry's knowledge. And the sophistication of its operational procedures has evolved in response to the variety of specialised forms of tourism.

Land-based tourism, some of it conducted from tour vessels, includes camping, mountaineering, skiing, and diving, and a temporary summer facility in the interior of Antarctica, at Patriot Hills in the Ellsworth Mountains, allows adventurers to be flown to the South Pole, or ski to it from Patriot Hills, as well as to visit Emperor Penguin colonies for stays of a week or more.

HOW IT WORKS

The collective experience of the current tour operator community (in total some 1500 years) over a period of some 35 actual years is a major factor in determining how and why the system works, with major attention given to preservation of the environment. As part of IAATO's original organisation, bylaws were compiled to identify the organisation's objectives and specify instructions and guidelines for operation, many of them related to Treaty Recommendation XVIII-1 from the Kyoto ATCM in 1994 (Antarctic Treaty Consultative Meeting 1994).

Membership categories were added to the bylaws to accommodate the increase in the numbers of vessels and their types, together with site guidelines specifying the numbers and sizes of ships permitted to visit locations to avoid over-visitation and potential impact on the wildlife. The limit of no more than 100 passengers ashore at any one place at any one time remains a guideline for any landings, together with a staff to passenger ratio of 1:20 while ashore. The basic guideline of IAATO's form of operation for its members remains: "To Advocate, Promote and Practise Safe and Environmentally Responsible Private-Sector Travel to Antarctica" (IAATO 2007a). These intentions remain the same wherever IAATO members operate, not only in Antarctica and the sub-Antarctic islands of New Zealand and Australia north of the Antarctic Treaty area, but also other southerly areas in their operations, such as South Georgia, South Sandwich Islands, Falkland Islands/Islas Malvinas. Many of the same IAATO member-operators also have comparable cruises in the Arctic and sub-Arctic, and observe the same guidelines and bylaws. A strong educational focus remains as a major theme of tour vessel operations

MANAGEMENT INITIATIVES

Examples of IAATO management initiatives in recent years to address the growth of tourism and required precautions include the following relevant to tourism in Antarctica and the sub-Antarctic islands.

Ship-scheduler and vessel call data

In order to organise ship operations better and more efficiently, an online Ship-Scheduler plan was developed for operators to provide their choices of sites on a pre-assigned date and a first-come first-served basis to avoid overcrowding of sites. While pre-scheduling has almost always been part of IAATO's operational procedures the online option has greatly enhanced the organisation's ability to manage tourism and landings. Vessel contact information is updated each year and as needed to ensure that ships are in daily contact with each other for itinerary coordination and emergency contingency planning. There are IAATO mandatory procedures for ships to coordinate with one another.

Emergency medical evacuation response

A Vessel Data Base was developed to provide vessel and company information in order to assure preparedness for possible emergency situations. An Emergency Medical

Evacuation Response (EMER) was developed to account for medical emergencies.

Improved operating database

Hydrographic charting has become a normal activity for all tour vessels in little-known areas in an effort to improve charts. Other ship-borne procedures provided for tour vessels include a restriction on ballast-water release in the Antarctic Treaty area, and improved communications among all operators.

Wildlife watching guidelines

Procedures related to wildlife include Marine Wildlife Watching Guidelines, a parallel of that in place for wildlife on land, and include guidelines, for example, on safe distances from birds.

Alien species

An important aspect of IAATO guidelines is concern about the introduction of alien species. Guidelines covering this have been in place since IAATO's eleventh Annual General Meeting in Hobart, Tasmania (2000) and consist of boot and clothing decontamination guidelines, briefings to passengers and crew on translocation of diseases, procedures on boot-washing stations on ships and ashore, and the use of Virkon or equivalent disinfectant solution for washing. This is a particularly important procedure for all visitors to Antarctica to follow because of itineraries that include sub-Antarctic islands where seeds and related material might adhere to clothing and boots and possibly be introduced into Antarctica.

Accreditation and auditing

Accreditation and auditing procedures are under development in order to illustrate that what IAATO says it does can actually be demonstrated in a transparent manner. An observer program exists on ships to oversee operational activities including passenger and crew briefings, boot-washing procedures to prevent introduction of alien organisms into the Treaty Area and between shore visits, and other precautions. The observer program also contributes to information about possible minor or transitory environmental impacts.

THE LEGACY OF IAATO

IAATO has proven itself to be a successful manager of Antarctic tourism as a result of many of its initiatives, and by exhibiting a non-harmful presence in Antarctica. Support for these contentions has been provided by Treaty Party delegates in Antarctic Treaty Consultative Meetings. Details of management are removed from Treaty Party direct involvement, (i.e., IAATO is self-managing) but the parties are welcome to oversee the process and act accordingly when new regulations or procedures are required. Treaty parties are welcome to regulate tourism, and endorse the proactive approach that IAATO has taken in managing tourism. Continuing dialogue is an important part of this process.

The contribution of IAATO to the sub-Antarctic and Antarctic is illustrated in the following activities.

Science-assisted logistics

Transport of science/support personnel to and from stations and/or field sites — the "Ships of Opportunity" advantage of tour ships that visit many places in the sub-Antarctic and Antarctic that Treaty Party vessels might visit. About 100 science and support personnel per year are transported, many of them in the Ross Sea sector, and, for example, to and from Macquarie Island and Heard Island. Personnel were also transported to Campbell Island when the station was occupied. Tourism, rather than viewing itself as an entity completely isolated from science and research in Antarctica (the mandate stated in the Antarctic Treaty), has adopted and developed a longstanding outreach policy of assisting science.

Charitable assistance

IAATO member companies and their passengers contribute annually towards a number of charitable organisations, such as Save the Albatross Campaign, Antarctic Heritage Trusts for UK huts in the Antarctic Peninsula area and New Zealand huts in the Ross Sea sector, Grytviken Whaling Museum, Orca Project, American Bird Conservancy, Oceanites, and Birdlife International – Albatross. Donations of some US$350 000 were contributed in the 2005–2006 austral summer.

Donations raised through the charging of passenger fees in the sub-Antarctic islands of New Zealand and Macquarie Island provide the means to improve the facilities on the islands and assist towards management expenses by their respective governments. Boardwalks on Campbell Island and viewing platforms on Macquarie Island are tangible examples of how some of those funds are used. Mawson's Hut at Commonwealth Bay is also a major target of contributions for those who realise the need to preserve these historic records of earlier exploration and science.

Ambassadors

Perhaps less tangible but still effective is the principle that passengers who visit the sub-Antarctic and Antarctic can become "ambassadors", taking back with them a record of the majesty of this remote region and what it offers in wildlife, and the need for overall protection. Those philosophies are often reflected later in lobbying for legislation to protect Antarctica, further donations towards worthy causes, and the like.

Partnership with Treaty parties and related organisations

IAATO believes in the philosophy that creative and successful work can be accomplished between the science community and tourism by continuing dialogue with Treaty parties, the Council of Managers of National Antarctic Programs (COMNAP), and the Scientific Committee on Antarctic Research (SCAR), providing input at ATCMs in its Expert Status category. Co-operation with international agencies such as the International Hydrographic Organization-Hydrographic Committee on Antarctica (IHO-HCA) in the improvement of charting for safe navigation is also seen as important.

FUTURE OF IAATO AND POTENTIAL CONCERNS

Although the relationship between IAATO, governments responsible for the management of the sub-Antarctic islands and the Antarctic Treaty parties has been relatively smooth, and is improving, there are occasional inconsistencies in government interpretations of tourism management. In some cases governments adopt the principle that what has been proper for management of its own territory and national parks, for instance, should be proper for management of

tourism in Antarctica. A closer working relationship could benefit the long-term effectiveness of managing remote areas. Discussions are necessary between all stakeholders and are needed in the quest to find compromises, or to direct useful efforts towards a common working objective.

Media concerns are another facet of the tour industry; incidents can sometimes be reported erroneously or blown out of proportion. Some journalists are prone to seize on a minor event and expand on it to illustrate inaccuracies or concerns in a manner that is not realistic. The consequence is often that tourism is presented as unregulated or poorly managed. Self-imposed guidelines have been adequately developed and fully adhered to since 1991 when IAATO was formed (Splettstoesser & Folks 1994, Splettstoesser 1996).

IAATO is concerned about non-member operators. IAATO will continue to encourage any operators not presently members of IAATO to join. The need for communication and cooperation between operators working in polar regions is paramount. Operators who are newcomers to the sub-Antarctic islands and Antarctica need to work together and take account of the permit procedures of their native countries in addition to those agreed by the Antarctic Treaty. They need to carry out operational procedures necessary for visits not only to the Antarctic continent but also the sub-Antarctic islands, where wildlife and vegetation, as well as alien organisms, are consistently major concerns

Governments that administer Antarctic islands should be urged to exchange experiences and information on tourism management. Close links should be established among tourist operators, tour company associations, island management authorities, and the scientific and conservation community, to promote responsible and safe operations (International Union for the Conservation of Nature 1992).

Future challenges and identified tasks are as follows and require further discussion amongst appropriate parties.

- Concern that an increase in tourism causes environmental impact. Does it? Could it? If so, to avoid such impacts requires a close working relationship between all stakeholders. Bridging these efforts needs to be further identified.
- Should science be involved in decision-making, for example in determining accurate information on the possibility that cumulative impacts occur in wildlife areas visited by tourists on a frequent basis? Without science backing, are any regulatory decisions in this regard credible?
- Different landing sites need different management strategies. Identify particular areas that could be of potential risk and work cooperatively to ensure that best practices are identified.
- What lessons can be learned from management practices in effect for many years in sub-Antarctic islands that can be applied to Antarctic Treaty areas visited by tourists?
- Costs of management of remote areas increase annually. Creative ways of ensuring protection must be examined without incurring enormous costs if other alternatives are possible.
- Ensure, where possible, that environmental considerations prevail over political agendas. This could perhaps be one of the most difficult areas to address.
- What can be learned from management plans at each of the sub-Antarctic island groups and where are the management gaps?
- Would a global and or localised environmental steering group be useful for decision-making?
- Would a website discussion forum be useful to examine management procedures in sub-Antarctic islands and enhance existing management plans?

CONCLUSION

IAATO has managed the tourism industry in Antarctica and the sub-Antarctic islands successfully for the 15 years of its existence. The organisation wrote and implemented numerous guidelines and operating procedures that were developed by its members over many years, all with protection of the environment in mind As a result, little, if any, discernible environmental impact is evident.

The procedures used presently extend to other areas (Arctic, sub-Arctic, Amazon, all other continents) thus emphasising protection of the environment. All IAATO activities are reported annually and transparently and Antarctic Treaty parties look to IAATO for discussions that assist in the resolution of tourism issues.

IAATO is committed to the long-term protection of Antarctica, the sub-Antarctic islands and associated and dependent ecosystems and looks forward to future cooperation wherever and whenever possible, with respect to activities in not only the Antarctic Treaty area, but also in the sub-Antarctic islands

ACKNOWLEDGEMENTS

IAATO would like to thank Sir Guy Green for his life-long passion and dedication towards protecting one of the most incredible parts of the world, the sub-Antarctic islands and Antarctica, Professor Pat Quilty and Dr Patricia Selkirk for their patience and contributions towards organising the speakers' presentations for publication, and Antarctica Tasmania (Ben Galbraith and Heather Glidden) for organising this very important conference on the sub-Antarctic. Government organisations of this nature play an integral role in protecting the wild places which are vitally important to the health of the planet. This paper and its presentation at the meeting of the sub-Antarctic islands in Hobart has benefited from contributions by many IAATO members, but in particular from John Splettstoesser, Advisor to IAATO.

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AFTERWORD

The premise upon which this Forum was based was that the sub-Antarctic islands and the surrounding seas comprise a distinct domain which has its own unique character, scientific significance and management issues. Encapsulated in the paper by Dr Patricia Selkirk *The Nature and Importance of the sub-Antarctic* and elaborated in other papers, the Proceedings of the Forum published in this volume amply vindicate that perception of the sub-Antarctic. The characteristics of the vast Southern Ocean — the only ocean to circulate around the entire globe, the special nature of the biota, geology and climate of the sub-Antarctic islands and the complexity of the intersecting legal and management regimes which govern them, all justify characterising the sub-Antarctic as a truly distinct and special domain.

The special qualities of the region are epitomised by the fact that Heard and McDonald islands, Macquarie Island, and the five island groups comprising the New Zealand sub-Antarctic islands are World Heritage sites and the Prince Edward Islands are being considered for inclusion. The diversity of the qualities of those islands is illustrated by the fact that the justification for their inclusion in the list of World heritage sites is different in every case ranging from a rare pristine island ecosystem and the best exposed seafloor in the world through to islands remarkable for their high level of biodiversity and endemism.

The Forum concluded with a discussion with the objectives of identifying areas where more research was needed and exploring ideas about the future of the region.

The exchange and recycling of nutrients between the terrestrial and marine environments of the sub-Antarctic was shown to be an especially fertile field for further research; areas inadequately covered include studies of the role of seabirds in recycling nutrients and the impact on nutrient cycling of the large fluctuations over time in the populations of species such as fur seals. Other promising fields include investigating the effects of climate change on biodiversity and the functioning of the ecosystems through monitoring and the establishment of data bases, oral history and the photographic record; elucidating variations in the earth's mantle and the processes driving the formation of Earth's magnetic field by integrating observations made on sub-Antarctic islands with the data derived from satellites and observatories elsewhere in the world; undertaking studies by evolutionary biologists and biogeographers of the establishment of species on the islands of the region and the transport of species between them; identifying the alien species established over the last 200 years through human activity including, in particular, invertebrate groups about which little is known and microbial groups about which virtually nothing is known and investigating the special geological properties of sub-Antarctic islands which are a function of their recent and diverse origins and — save for South Georgia — their character as authentic islands in that they are not and have never been part of continents.

It was recognised that an impediment to the doing of much of the further sub-Antarctic research which is needed is the difficulty of obtaining funding for programmes entailing monitoring and data collection which extend over periods longer than the usual funding cycles and which are not prolific producers of publications. It was concluded that generally speaking the only long term monitoring programmes that survive are those which are owned by an institution rather an individual.

It also was concluded that even if it were practicable there is no sufficient occasion for the establishment of a comprehensive regime governing the sub-Antarctic comparable to the Antarctic Treaty System. However significant gaps in the legal regime affecting the region were identified and the question was raised whether or not there should be a more comprehensive approach to looking at the Southern Ocean as a distinct regime and establishing an oceans governance framework for it.

There was a strong consensus that the Forum had been a successful experiment and that — as well as the quality of the participants — its success was attributable to it being non political and multidisciplinary and to it being founded upon the recognition of the sub-Antarctic as a distinct domain.

The Forum was not formally constituted as a decision-making meeting but actions indicated by it include:

- promoting the inclusion of sub-Antarctic research and long term monitoring programmes in existing programmes and institutions or the establishment of new programmes or institutions for the purpose
- establishing the holding — say biennially — of a sub-Antarctic Forum as a permanent fixture
- using <www.sub-antarctic.org> as a vehicle for lifting the profile and coordinating the management of the sub-Antarctic and exchanging information and facilitating dialogue about it
- finding a new name for the region consonant with its status as a distinct entity rather than an appendage of Antarctica. This is not a trivial exercise. The naming of the geographic zones of the Earth is not a mere matter of labelling but like all taxonomies identifies them as distinct entities and helps define their properties and their place in the world. Peri-Antarctic or Circum-Antarctic have been suggested in the past but have not gained currency. Perhaps the time has come to sever the Antarctic association entirely and think in terms of something like The Great Southern Zone.

Sir Guy Green (Chairman of the Forum)

PAPERS AND PROCEEDINGS OF

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PAPERS AND PROCEEDINGS OF THE ROYAL SOCIETY OF TASMANIA

Volume 141, Part 2

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Publication of this volume was generously supported by the Government of Tasmania and the University of Tasmania.

CONTRIBUTIONS TO A CATALOGUE OF ALIEN PLANTS IN TASMANIA II

by Matthew L. Baker

(with two text-figures, six plates and one table)

Baker, M. L. 2007 (23.xi): Contributions to a catalogue of alien plants in Tasmania II. *Papers and Proceedings of the Royal Society of Tasmania* 141(2): 187–196. ISSN 0080-4703: Tasmanian Herbarium, Tasmanian Museum and Art Gallery, Private Bag 4, Hobart, Tasmania 7001, Australia.

The status of six alien plant taxa recorded in Tasmania is discussed. *Disa bracteata* Sw. is a new incursion that has been recorded once in Tasmania; further evidence is required to determine its status. *Acer pseudoplatanus* L., *Griselinia littoralis* (Raoul) Raoul, *Leonotis leonurus* (L.) R.Br., *Persicaria capitata* (Buch.-Ham. ex D.Don) H.Gross and *Rhododendron ponticum* L. are ornamental taxa that are now recognised as naturalised in Tasmania. A description for each taxon is provided and distribution and habitat details are discussed. A key to the Tasmanian species of *Persicaria* (L.) Mill. is included. Name changes of six naturalised species are provided: *Moraea flaccida* (Sweet) Steud., *Hesperantha coccinea* (Backh. & Harv.) Goldblatt & J.C.Manning, *Lepidium draba* L. subsp. *draba* L., *Lepidum didymum* L., *Lepidium squamatum* Forssk. and *Nasturtium officinale* R.Br.

Key Words: naturalised, incursions, exotic, weeds, introduced flora, Tasmania.

INTRODUCTION

Management of Tasmania's alien flora requires an accurate and up-to-date account of taxa present. This paper is the second part of a series (Baker 2005) aiming to ensure that taxa which become naturalised in Tasmania are formally recorded; that taxa that are present in Tasmania, but have not become fully naturalised ("sparingly naturalised" in the sense of Buchanan (2005) and Baker (2005)) are likewise recorded; that new incursions of alien taxa are recorded; and to maintain up-to-date names for taxa that have been affected by nomenclatural change. In this paper, six taxa are treated, giving diagnostic descriptions and notes on their distribution. Name changes for six naturalised taxa are presented. It is hoped that this information will increase general knowledge of distribution of naturalised alien taxa in Tasmania and raise community awareness of plants that have the potential to become naturalised.

Reports of new incursions, naturalised and sparingly naturalised species are welcomed by the author. Specimens and relevant collection information can be forwarded to the Tasmanian Herbarium.

MATERIALS AND METHODS

Primary sources used for this study are specimens held in the Tasmanian Herbarium (HO). Herbarium abbreviations follow Holmgren *et al.* (1990). Identifications by the author and others were checked against the literature and, where available, reliably identified voucher specimens.

Voucher specimens for all species treated have been lodged in the Tasmanian Herbarium. The naturalised status of treated species is based upon field observations made by the author and others and, when available, from notes accompanying specimens.

Citations of synonyms are limited to names used in the Tasmanian literature. Tasmanian distributions follow floristic regions proposed by Orchard (1988). Geographical origins of plants treated have been determined from various published sources. Definitions of "alien" and "naturalised" and "sparingly naturalised" have been discussed by Baker (2005). "New incursions" are newly recorded alien species that are not regarded as naturalised. They are usually accidental introductions known from small localised populations or single plants that have been present only for a short duration. Whether these species become fully naturalised or are transient only remains to be seen. "Sparingly naturalised" species differ from "new incursions" in that they are known from more than one population and have persisted for a longer duration; such species frequently represent deliberate introductions, for example as garden plants. Evidence suggests that these species are showing likely, but not conclusive, signs that they will become naturalised.

NEW INCURSIONS

1. *Disa bracteata* Sw., *Kongl. Vetensk. Acad. Nya Handl.* 21: 211 (1800). (Orchidaceae)

Common names: South African orchid, South African weed-orchid.

Illustrations: Blood (2001: 173); Cochrane (2001: 31); Jones (1988: 416; 2006: 478); pl. 1.

Description: Deciduous terrestrial herb, to 40 cm tall with fleshy tubers. Leaves cauline, usually crowded at base; lamina narrow-lanceolate, green, sometimes with reddish margins and apex, to 15 cm long and 1.5 cm wide, with a broad sheathing base. Inflorescence a many-flowered spike. Flowers small, *c.* 5 mm diam., greenish-white, with the extremities of larger segments reddish-brown; bracts leaf-like, shorter than to longer than the flowers; dorsal sepal hood-like, with a retrorse basal spur to 5 mm long, 1.5 mm wide; lateral sepals spreading; petals erect, partially enclosed within the dorsal sepal; labellum to 3.5 mm long, yellow. Ovary to 7 mm long. Seeds minute.

Other descriptions can be found in Jones (1988, 2006).

Discussion: *Disa* P.J.Bergius is a genus of 99 species of terrestrial orchids, native to tropical and southern Africa, Arabia, Madagascar and the Mascarenes (Mabberley 1997).

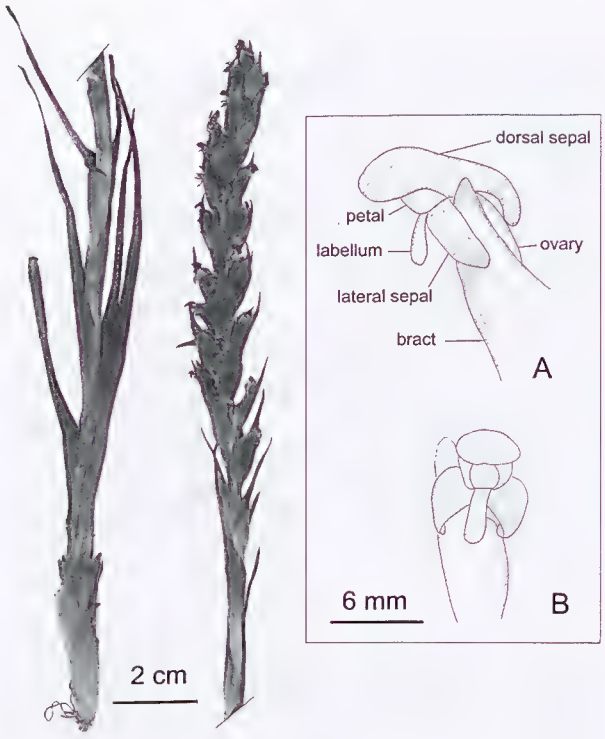

PLATE 1
Habit of Disa bracteata *(lower section left, upper section right); Inset: flower detail, (A) lateral view, (B) front view.*

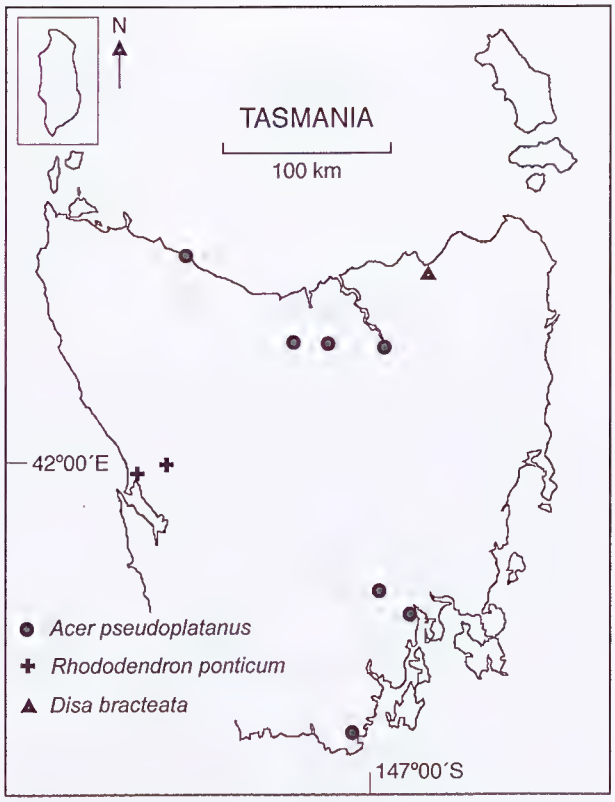

FIG. 1 – Geographical distribution of Disa bracteata, Acer pseudoplatanus *and* Rhododendron ponticum *as known from herbarium specimens.*

One species, *D. bracteata* (previously known as *Monadenia bracteata* (Sw.) Durand & Schinz), is naturalised in Australia.

Disa bracteata has a range of floral characteristics that allow it to be easily differentiated from native orchid species. These characteristics include dorsal sepals with a downward pointing basal spur, a narrow, yellow, tongue-shaped labellum, and a prominent leaf-like bract that subtends each flower; the latter is also present in native orchids, for example, *Orthoceras strictum* R.Br. The leaves, although cauline, appear to form a loose rosette. Flowering occurs from October to December.

To identify the species from other Tasmanian orchids the following key couplets can be inserted into Jones *et al.* (1999: 35) "Key to the Genera".

Addendum to key to the genera of Orchidaceae in Tasmania

10. Leaf cylindrical, solitary, hollow. Flowers green or yellowish green, not arranged in a prominent spiral; sepals and petals free and spreading; labellum margins entire or with granular excrescenses..... ***Microtis***
10: Leaves linear, several, not hollow. Flowers without the above combinations of characters 10a
10a. Dorsal sepal without a spur at the base. Flowers dense, usually arranged in a distinct spiral, pink, rarely white; labellum white..... ***Spiranthes***
10a: Dorsal sepal with a prominent retrorse basal spur. Flowers very dense, not arranged in a distinct spiral, larger segments greenish-white with reddish-brown extremities; labellum yellow..... ***Disa***

Distribution and habitat: *Disa bracteata* is endemic to the Western and Eastern Cape Provinces of South Africa (African Flowering Plants Database 2006). In Western Australia, it is a common weed throughout the southwest region from Perth to Esperance (Jones 1988). In South Australia, it occurs in the Southern Mt Lofty, Northern Mt Lofty, Murray and South-Eastern regions (Barker *et al.* 2005). In Victoria, it is known to occur in numerous locations, from Gippsland in the east to the state border in the west. In Tasmania, it is known from only one specimen collected from a grassy roadside verge near Bridport in the state's North-East region (fig. 1). This represents the first Tasmanian record of an exotic orchid growing outside cultivation. Collection information indicated that a small population of plants were present. However, the collection site and local area were re-surveyed in December 2005 and twice in November 2006 but the species was not found again. In Australia, *D. bracteata* is commonly associated with moist and disturbed soils, in habitats including woodland, grassland, roadside verges and paddocks. *Disa bracteata* is a self-pollinating species. Plants produce large numbers of very fine seed that is transported readily by wind and may be spread as a contaminant on clothing, vehicles and equipment. From the history of its spread in other states, it is likely to appear at other localities in Tasmania where suitable habitats occur.

First record: 2005, A. Jungalwalla & D. Farmery.

Specimens examined: **TASMANIA**: *North-East region*: Bridport Road, 4 km SE of Bridport, 14 Nov. 2005, *A. Jungalwalla & D. Farmery s.n.* (HO). **VICTORIA**: Parwan Valley, White Elephant Reserve, 3.5 km NNW from Glenmore Road access point to Reserve, Glenmore (10 km W of Bacchus

Marsh PO), 4 Nov. 2000, *V. Stajsic* 2136 (AD, CANB, HO, MEL, NSW).

NATURALISED TAXA IN TASMANIA

2. *Acer pseudoplatanus* L., *Sp. Pl.* 1054. (1753). (Aceraceae)

Common name: sycamore maple.

Illustrations: Blood (2001: 13); Muyt (2001: 231–232); Walsh (1999: 151, fig. 27b); pl. 2.

Description: Trees to 20(–30) m tall. Shoots opposite, glabrous. Leaves opposite, deciduous; petiole 5–17(–22) cm long; lamina palmately (3–)5-lobed, 9–16(–20) cm long, 9–18(–27) cm wide, green adaxially, glaucous abaxially with hairs confined to the main veins; lobes ovate; margin irregularly and coarsely toothed; base usually cordate. Inflorescence a pendant, many-flowered racemose panicle to 22 cm long. Flowers small, on pedicels to 13 mm long; sepals and petals similar, greenish-yellow, *c.* 3 mm long, oblong; stamens usually 8; ovary white-woolly. Fruit a schizocarp of two joined samaras; samara wings to 5 cm long, usually spreading at an obtuse angle, reticulate. Seeds 5–10 mm long.

Discussion: *Acer* L. is a genus of 111 species, native in mountainous regions throughout the Northern Hemisphere (Mabberley 1997). Several species are common in cultivation, including *A. negundo* L. (box elder), *A. pseudoplatanus* and numerous cultivars of *A. palmatum* Thunb. (Japanese maple); the former two species are naturalised in Australia (Walsh 1999). *Acer palmatum* is listed as "incipiently naturalised" in Victoria (Ross & Walsh 2003). In Tasmania, Raphael (1955) recorded *A. pseudoplatanus* as an occasional "garden escape" in suburban habitats, and recent mainland floras (e.g., Walsh 1999, Hewson 1985) regard *A. pseudoplatanus* as naturalised in Tasmania. There are no herbarium voucher specimens to validate Raphael's observations. However, several recently collected specimens indicate that *A. pseudoplatanus* is fully naturalised in the state and is invasive and dominant in some locations.

Acer pseudoplatanus is recognised by its deciduous habit, oppositely arranged branches and leaves, and fruit comprising two fused, winged samaras. As many as 30 fruits per panicle are formed. In sheltered situations, the fruits may remain on the tree throughout winter. *Acer negundo,* which is sometimes cultivated in Tasmania but is not naturalised, differs by having pinnately divided, as opposed to palmately lobed leaves.

Distribution and habitat: *Acer pseudoplatanus* is native to central and southern Europe (Walters 1968). It is cultivated for shelter and ornament throughout the world, especially in cooler climates and is widely naturalised, for example, in Britain, Denmark, Ireland, Sweden (Walters 1968), North America (Gleason 1968), New Zealand (Sykes 1988a) and Australia. Seed is dispersed by wind, and may be carried distances of up to 85 m from parent plants (Jones 1945). Seed germinates readily in both dense shade and open sites, although young plants do not tolerate competition (Jones 1945). In New Zealand, it is has become naturalised in a range of habitats including scrub bordering roadsides and rivers and in and around forest. In mainland Australia, it is naturalised as a garden escape in New South Wales, Victoria and South Australia (Blood 2001, Muyt 2001). In Tasmania, *A. pseudoplatanus* is naturalised at several sites across the state (fig. 1). It is most commonly associated with moist shady habitats, occurring singly or in very large populations in drainage lines on roadsides, on the banks of watercourses, and in damp, sheltered forest. In some situations, forests composed almost entirely of *A. pseudoplatanus* have been recorded. One example is parts of the Cataract Gorge (Launceston) where seedlings and small plants make up the understorey and large mature trees the canopy.

PLATE 2
Fruiting branch of Acer pseudoplatanus.

First record: 2002, M. Wapstra.

Specimens examined: **TASMANIA**: *East Coast region*: New Norfolk, 5 Nov. 2003, *A.M. Buchanan* 16076 (HO, MEL). Hobart, Sandy Bay Rivulet at Romilly Street bridge, 10 Feb. 2006, *M.L. Baker* 1698 *& A.M. Buchanan* (HO). *North-West region*: Bass Highway, between Tolymore Road junction and Costelloes Road junction, 2 Nov. 2004, *M.L. Baker* 988 *& M.F. Duretto* (HO). *Midlands region*: Cataract Gorge, Maple Steps. Launceston, 14 Oct. 2005, *M.L. Baker* 1645 (HO). "Armitstead" property, 30 Oct. 2002, *M. Wapstra s.n.* (HO). Larcombes Road, 9 May 2002, *M. Wapstra s.n.* (HO). *South-West region*: Camping area near mouth of Catamaran River, 6 Nov. 2005, *M.F. Duretto* 1957 (HO, MEL). **ITALY**: Torino. Valli di Lanzo, Chiaves, 22 Jul. 1988, *R. Camoletto* 2091 (HO, MRSN).

3. *Griselinia littoralis* (Raoul) Raoul, *Choix Pl. Nouv.-Zél.*: 22, t. 19 (1846). (Griseliniaceae)

Common names: broadleaf, kapuka.

Illustrations: Salmon (1980: 264–265); pl. 3.

Description: Large shrubs to medium trees to 17 m tall, dioecious. Young stems golden-yellow to olive-green, becoming grey-brown with age. Leaves glabrous, alternate; petioles 8–35(–40) mm long, partially sheathing the stem; base oblique to equal; lamina leathery, elliptic to orbicular or ovate, 30–90(–133) mm long, 20–65(–13) mm wide, with adaxial surface glossy green and abaxial surface less glossy and pale yellow-green; margin entire, revolute; apex rounded to obtuse or emarginate. Staminate inflorescences paniculate, to 50 mm long. Staminate flowers small on pedicels to 2 mm long; sepals 5, minute; petals 5, *c.* 1 mm long; stamens 5, less than 1 mm long, attached to a glandular disc located at the centre of the flower. Pistillate inflorescences paniculate or racemose, to 70(–100) mm long. Pistillate flowers on pedicels to 7 mm long; sepals and petals as per staminate flowers; styles 3. Fruit obovoid, *c.* 6 mm long, *c.* 4 mm wide, green at first, maturing black, 1-seeded.

For a comprehensive treatment of *Griselinia* J.R. Forst. & G. Forst. see Dillon & Muñoz-Schick (1993). Plant height, inflorescence length and fruit characteristics in the above description are taken from Dillon & Muñoz-Schick (1993).

Discussion: *Griselinia* is a genus of seven species native to New Zealand (2 spp.) and Chile (5 spp.). It is the sole genus within the family Griseliniaceae, although some authors place it in the family Cornaceae (e.g., Cronquist 1981, Mabberley 1997).

Griselinia littoralis superficially resembles the naturalised shrub, *Coprosma repens* A.Rich. (Rubiaceae), both species having leathery leaves with a glossy adaxial leaf surface. However, the two species can easily be distinguished by their leaf arrangement: *C. repens* has opposite leaves whereas *G. littoralis* has alternate leaves.

Distribution and habitat: *Griselinia littoralis* is endemic to New Zealand, where it is found in a wide range of habitats from lowland forest through to sub-alpine scrub to 3200 m (Dillon & Muñoz-Schick 1993, Burrows 1995). Naturalised populations of *G. littoralis* were recently discovered in remnant bushland within the township of Strahan, the source of the naturalised plants being cultivated specimens from gardens in the surrounding area. This is the first record of this species being naturalised in Australia. In one of the populations, plants were growing in an area of disturbed bushland in association with *Acacia melanoxylon* R.Br., *Melaleuca ericifolia* Sm., *Tasmannia lanceolata* (Poir.) A.C.Sm. and naturalised species, including *Cotoneaster simonsii* Baker, *Ilex aquifolium* L. and *Rubus fruticosus* L. *sens. lat.* Plants ranged in size from small seedlings through to large adult plants estimated (by ring counts from several of the largest plants) to be about 25 years old. The species was not observed to be highly invasive or dominant, instead having a scattered distribution. In some situations in New Zealand, it is known to be opportunistic, dominating areas after disturbance events such as fire and landslides (Burrows 1995). Fruits of *G. littoralis* are eaten and dispersed by birds (Burrows 1995).

PLATE 3
Branch of Griselinia littoralis *with pistillate inflorescence.*

Griselinia littoralis is not commonly available through the nursery industry and garden plantings are uncommon in Tasmania. However, it is promoted in several horticultural tomes (e.g., Huxley 1999, Philips & Rix 2002, Spencer 2002) as a useful hedging and windbreak species, particularly suited to coastal situations, as it tolerates strong maritime winds; several cultivars are mentioned including variegated ones.

First record: 2005, T. Rudman.

Specimens examined: **TASMANIA**: *West Coast region*: Strahan, W side of Customs House, 1 Nov. 2005, *T. Rudman s.n.* (HO). Strahan, remnant forest behind Post Office, 21 Nov. 2005, *M.L. Baker* 1670 (AD, CANB, HO, MEL, NSW). Strahan, Hogarth Falls Peoples Park, 21 Nov. 2005, *M.L. Baker* 1666 (HO). *East Coast region*: Royal Tasmanian Botanical Gardens (cultivated), Hobart, 13 Jan. 2006, *M.L. Baker* 1695 (HO). **NEW ZEALAND**: Reefton Saddle, Reefton, Dec. 1965, *A.M. Buchanan s.n.*(HO). North Canterbury, road to Lake Taylor on road verge, 23 Jan. 1985, *J. Glasson* 66 (CHR, HO). Franz Josef, South Westland, 27 Sep. 1967, *A.M. Buchanan s.n.* (HO). South Otago, inland from Purakaunui Bay, 13 Feb. 1985, *E.D.W. Freeman* 85/22 (CHR, HO). Near Cabstand, Akaroa, Banks Peninsula, 3 Nov. 1980, *M.J.A. Simpson* 8306 (CHR, HO).

4. *Leonotis leonurus* (L.) R.Br. *Hortus Kew. (W.T. Aiton)*, ed. 2(3): 410 (1811). (Lamiaceae)

Common name: lion's tail.

Illustrations: Macoboy (1989: 236); pl. 4.

Description: Erect shrubs to 2(–5) m tall. Stems quadrangular, with each face bearing a longitudinal groove, densely covered with sessile glands and antrorsely appressed hairs, becoming glabrous with age. Leaves opposite, shortly petiolate, linear, 3–10 cm long, 1–2 cm wide; adaxial surface green, with scattered hairs and glands; abaxial surface paler green, with glands scattered but hairs mostly confined to veins; base attenuate; margin serrate in distal half; apex acute. Inflorescence of several, distantly-spaced, many-flowered false-whorls, with each whorl subtended by a pair of leaf-like bracts. Flowers subtended by linear bracteoles, each bracteole to 20 mm long and *c.* 1 mm wide; pedicels to 7 mm long; calyx tubular, to 14 mm long, 5–7mm wide, with 6–10 short spreading teeth. Corolla two-lipped, to 50 mm long, curved, with a dense covering of orange hairs; upper lip to 20 mm long; lower lip with 3 short lobes each c. 2–3 mm long. Stamens 4. Fruit of 4 nutlets.

For a comprehensive treatment of *Leonotis* (Pers.) R.Br. see Iwarsson (1985).

Discussion: *Leonotis* is a genus of 15 species from tropical Africa. One species, *L. nepetifolia* (L.) R.Br., extends to America and Asia and is widely naturalised in subtropical regions of the world (Mabberley 1997) including Australia. Several species, including *L. leonurus,* are widely cultivated as garden plants (Huxley 1999).

Leonotis leonurus is a distinctive species especially when flowering. The orange colour of the corolla is due to a dense covering of fine, orange hairs. A form with a white corolla also exists but is less often seen in cultivation and is not known to be naturalised in Tasmania. The flowers are usually arranged in distantly-spaced clusters along erect stems. At very dry sites (e.g., Opossum Bay, Tasmania), the inflorescence may be represented by a single, terminal cluster.

Distribution and habitat: *Leonotis leonurus* is native to South Africa, where it is recorded from a wide range of habitats including forest margins, river banks, rocky hillsides and grassland from sea level to 2000 m (Iwarsson 1985). In Australia, it is widely cultivated and occasionally naturalised, usually as a garden escape in coastal situations in New South Wales, Western Australia, Victoria and Queensland (Richardson *et al.* 2006). The current edition of the Victorian Census of Vascular Plants (Ross & Walsh 2003) and the 8th edition (in prep) do not regard *L. leonurus* as being naturalised in Victoria (N. Walsh pers. comm.). In Tasmania, *L. leonurus* is occasionally found persisting in old gardens or arising from discarded garden refuse (e.g., A.M. Buchanan 16275). One recently recorded, naturalised population (at Opossum Bay (fig. 2)) had colonised the lee side of a low coastal fore-dune and was growing in association with introduced grass species, including *Ammophila arenaria* (L.) Link (marram grass). The *L. leonurus* population consisted of 30 to 40 plants (including seedlings), covering an area of approximately 400 m². The origin of the plants is unknown but it is possible that they

PLATE 4
Flowering branch of Leonotis leonurus*; inset: close up of flower.*

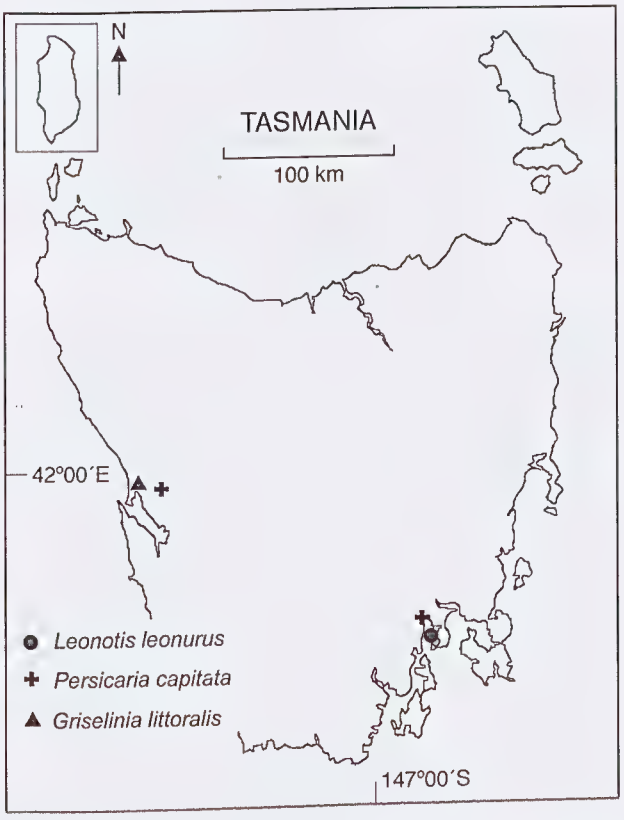

FIG. 2 – Geographical distribution of Griselinia littoralis, Leonotis leonurus *and* Persicaria capitata *as known from herbarium specimens.*

originated from dumped garden refuse. The species was also observed in cultivation in several gardens within 1 km of the site. Harris *et al.* (2001) records the species from Badger Island (Furneaux group) as persisting in an old garden.

First record: 2006, M. Wapstra (A.M. Buchanan 16275 predates this collection but is not considered to be truly naturalised).

Specimens examined: **TASMANIA**: *East Coast region*: Coles Bay, 25 Dec. 2004, *A.M. Buchanan* 16275 (HO). Arm End, South Arm, 12 May 2006, *M. Wapstra s.n.* (HO). Arm End Reserve, Opossum Bay, 27 May 2006, *M.L. Baker* 1714, *E.L. Baker & A.G Baker* (AD, HO, MEL, NSW). **NEW SOUTH WALES**: Grounds of the Tathra Amateur Fishing Club, Kianinny Bay, Tathra, 21 Mar. 1999, *G.W. Carr* 9903 (AD, BRI, CANB, HO, MEL, NSW, PRE).

5. *Persicaria capitata* (Buch.-Ham. ex D.Don) H.Gross, *Bot. Jarb. Syst.* 49: 277 (1913). (Polygonaceae)

Common name: pink-head knotweed.

Illustrations: Wilson (1990: 281; 2000: 281); pl. 5.

Description: Perennial mat-forming herb. Stems prostrate, rooting at the nodes, reddish, sparsely glandular pubescent. Leaves 10–35 mm long, 5–20 mm wide, ovate to elliptic, alternate; petiole to 4 mm long, often with a leaf-like projection at the petiole-ochrea junction; base attenuate; margin entire, ciliate; apex acute; adaxial surface green to reddish, usually with a dark crescent-shaped blotch, both surfaces glandular pubescent; ochrea tubular, 7–10 mm long, membranous, glandular pubescent, truncate. Inflorescence an ovoid or globose spike, to 10 mm long and 7 mm wide, solitary or several together; peduncle 1–4 cm long. Perianth segments 5, *c.* 3 mm long, pink. Nut brown, shiny, trigonous, *c.* 1 mm diam., *c.* 2 mm long, enclosed in the perianth.

For a comprehensive description see Sykes (1988c, as *Polygonum capitatum* D.Don).

Discussion: *Persicaria* Mill. is a genus of approximately 150 species found mostly in northern temperate regions of the world (Brandbyge 1993), but with an almost cosmopolitan distribution (Mabberley 1997). The genus has been treated in the past as *Polygonum* L. (e.g., Sykes 1988c, Li *et al.* 2003, Akeroyd 1996). Buchanan (2005) lists seven species for Tasmania, two of which, *P. lapathifolia* (L.) Gray and *P. maculosa* Gray, are naturalised aliens. Four species, *P. decipiens* (R.Br.) K.L.Wilson, *P. hydropiper* (L.) Spach, *P. praetermissa* (Hook.f.) H.Hara and *P. subsessilis* (R.Br.) K.L.Wilson are native. One other species, *P. prostrata* (R.Br.) Soják, is listed with uncertainty as to its origin (i.e., it is unknown whether it is introduced to Tasmania or indigenous.). A third alien species, *P. capitata*, a commonly cultivated rockery/ground cover species, was recently found naturalised at one location on the West Coast of Tasmania.

Persicaria capitata can be readily distinguished from other Tasmanian species by its low growing, mat-forming habit and by having flowers clustered in capitate inflorescences.

PLATE 5
Flowering stem of Persicaria capitata.

Key to the species of *Persicaria* in Tasmania

1. Some or all leaves hastate or cordate-sagittate ..... ***P. praetermissa***
1: All leaves narrowed at the base 2
2. Inflorescence an ovoid or globose head, no more than twice as long as wide 3
2: Inflorescence an elongate spike or spike-like raceme or panicle, more than four times as long as wide 5
3. Ochreas usually terminating in a green, toothed or lobed limb; perianth green ..... ***P. prostrata***
3: Ochreas without a green limb at the apex (*P. capitata* often has a leaf-like projection at the petiole-ochrea junction); perianth pink to whitish 4
4. Leaves ovate to elliptic, up to 3.5 cm long; perianth about twice as long as the nut; plants prostrate ... . ***P. capitata***
4: Leaves lanceolate, 3–15 cm long; perianth only slightly exceeding the nut; plants ascending to erect .... ***P. maculosa***
5. Perianth conspicuously or sparsely glandular 6
5: Perianth without glands 7
6. Inflorescence slender; perianth segments usually five; ochreas ciliate at apex ..... ***P. hydropiper***
6: Inflorescence stout; perianth segments usually four; ochreas not ciliate at apex ..... ***P. lapathifolia***
7. Inflorescences mostly axillary, dense, shorter or scarcely longer than the leaves ..... ***P. prostrata***
7: Inflorescences mostly terminal or terminating lateral branches, usually extending well beyond the leaves 8
8. Leaves uniformly green, with conspicuous stiff hairs that are long on the abaxial surface but short on the adaxial ..... ***P. subsessilis***
8: Leaves often with a dark blotch near the centre, apparently glabrous although sometimes with scattered

hairs especially on the abaxial surface, or with glandular dots, and the margins often with short, stiff, curved hairs 9

9. Inflorescence slender, 3–5 mm diam., with the groups of flowers distinct and not, or scarcely, overlapping ..... ***P. decipiens***

9: Inflorescence stout, 7–10 mm diam., with the groups of flowers crowded and overlapping ..... ***P. maculosa***

Distribution and habitat: *Persicaria capitata* is native to Asia where it is widespread (Li *et al.* 2003). It is naturalised in Japan and Taiwan (Hsu *et al.* 2004), in the Azores and northern Portugal (Akeroyd 1996), the United States of America (Hinds & Freeman 2005) and New Zealand (Sykes 1988c). In Australia, it is naturalised in New South Wales, South Australia, Queensland (Richardson *et al.* 2005) and Western Australia (Western Australian Herbarium 1998–). In Tasmania, one significant population occurs on the West Coast (fig. 2), confined to a mossy roadside verge and growing in association with several native and exotic herbaceous species. It was not found in the adjacent rainforest vegetation. The species is occasionally found naturalised in suburban situations, such as growing from cracks in footpaths and pavements near cultivated specimens.

First record: 2005, M.L. Baker, A.M. Gray & K. Stewart.

Specimens examined: **TASMANIA**: *West Coast region*: Mt Jukes Road, 100 m N of bridge over King River, 22 Nov. 2005, *M.L. Baker* 1671, *A.M. Gray & K. Stewart* (AD, BRI, CANB, HO, MEL, NSW). *East Coast region*: Lindisfarne, intersection of Shore Street and Esplanade, 25 Apr. 2006, *M.L. Baker* 1710, *E.L. Baker & A.G. Baker* (HO).

6. *Rhododendron ponticum* L., *Sp. Pl. ed.* 2. 1:562. (1762). (Ericaceae)

Common names: common rhododendron, Pontian rhododendron.

Illustrations: Phillips & Rix (1989: 142); Macoboy (1989: 343); pl. 6.

Description: Shrubs to 6 m tall. Leaves alternate, entire, glabrous, often crowded in false whorls at the ends of branches; petiole to 20 mm long, grooved adaxially; lamina narrow-elliptic to narrow-obovate, 30–150 mm long, 10–45 mm wide, often larger on young, rapidly growing plants, coriaceous, green and shiny on adaxial surface, paler green abaxially; margin faintly revolute; apex acute; base cuneate. Inflorescence a terminal raceme with up to 20 flowers forming large, showy balls to 15 cm wide. Flowers at first enclosed in dehiscent pubescent bracts, 5-merous; pedicels to 35 mm long, with scattered glandular hairs; calyx to 2 mm long; corolla campanulate, 35–50 mm long, mauve-purple with numerous small brownish spots on the upper lobes; tube pubescent inside; stamens 10; filaments 15–25 mm long, unequal, pubescent in proximal half; carpels 5, joined; ovary glabrous to sparsely pubescent, 5-locular; style to 35 mm long, curved upwards in distal half; stigma capitate. Fruit a woody capsule, about 15 mm long, dehiscing longitudinally from the apex. Seeds small, numerous.

PLATE 6
Flowering branch of Rhododendron ponticum.

Discussion: *Rhododendron* L. is a genus of approximately 850 species, native mainly in the temperate regions of the northern hemisphere. Species-rich areas include the Himalayas, southeast Asia and Malesia, with some species occurring in America, Asia Minor, Iberia and Australia (Mabberley 1997). In Australia, two species, *R. lochiae* F.Muell. and *R. viriosum* Craven, are native in the highland regions of tropical northern Queensland (Craven 2002). A third species, *R. ponticum*, has spread from cultivation and has become naturalised in New South Wales and Tasmania. *Rhododendron* is a diverse and widely cultivated genus, with over 20 000 cultivars registered by the Royal Horticultural Society. In Australia alone there are approximately 1500 commercially available cultivars (Spencer 1997).

Given that *Rhododendron* is a large genus, it is beyond the scope of this paper to provide a detailed key or character list to enable *R. ponticum* to be reliably identified from the vast number of species and cultivars. However, the following characters may assist in its identification: leaves evergreen, revolute in bud; inflorescences terminal on the shoots; corolla mauve-purple with brownish spots on the upper lobes.

Distribution and habitat: *Rhododendron ponticum* is native to Europe where it has a disjunct native distribution, with centres in the Iberian Peninsula in the west and the Pontic Alps in the east and also Lebanon (Huxley 1999, Popova 1972). It has been widely cultivated in Europe as an ornamental species and has become extensively naturalised in parts of northwestern Europe (Popova 1972). In the United Kingdom,

it is a highly competitive plant that is most invasive in areas that have suffered from some form of disturbance such as fire, forestry activities or grazing (Cross 1975, 1981). It invades a wide range of habitats, in particular disturbed woodland on acid soils, disturbed heathland and the margins of bogs (Cross 1975). In some situations, it is locally dominant both as the shrub layer of woods and in the open (Clapham *et al.* 1962) and is considered a serious weed in plantation forestry and at sites of special conservation interest (Colak *et al.* 1998). In New Zealand, it has been planted extensively and is naturalised on both the North and South islands, in habitats including scrub and shady woodlands and plantations near gardens. In some New Zealand situations, large persistent thickets occur (Sykes 1988b). In Australia, *R. ponticum* is naturalised in the Central Tablelands region of New South Wales (K.L.Wilson pers. comm. 2006, Hosking *et al.* in press) and in Strahan and Queenstown on Tasmania's West Coast (fig. 1). In Tasmania, only small populations and isolated plants have been recorded. The largest population occurs in Queenstown on an exposed south-facing, moss-covered embankment (approximately 400 m^2). At this site, plants range in size from small seedlings through to mature flowering shrubs to 2 m tall. At Strahan, isolated mature plants have been recorded growing in remnant *Melaleuca squarrosa* Donn ex Sm. scrub. In all cases naturalised plants occur in close proximity to cultivated plants.

First record: 2005, M.L. Baker, E.L. Baker & A.G. Baker.

Specimens examined: **TASMANIA**: *West Coast region*: Queenstown, hospital carpark, 22 Nov. 2005, *M.L. Baker* 1673, *A.M. Gray & K. Stewart* (AD, CANB, HO, MEL, NSW). Strahan, Featherstone Street, 21 Nov. 2005, *M.L. Baker* 1668, *A.M. Gray & K. Stewart* (HO). Queenstown, hospital carpark, 20 Feb. 2005 *M.L. Baker* 1540, *E.L. Baker & A.G. Baker* (HO, MEL). *East Coast region (cultivated)*: Woodbank nursery, 25 Feb. 2005, *M.L. Baker* 1558 *& A.M Buchanan* (HO). **PORTUGAL**: Sierra de Monchique, Foia, ladera oeste del Pico Foia, 8 Jun. 2001, *L. Medina* LM2275, *S. Nisa & M. Pardo de Santayana* (HO, MA).

NOMENCLATURAL CHANGES

Taxonomic work being conducted elsewhere has led to name changes that affect species naturalised in Tasmania. These are presented in table 1.

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TABLE 1
Current and previous names of some taxa naturalised in Tasmania

Current name	Previous name	Reference
Moraea flaccida (Sweet) Steud.	*Homeria flaccida* Sweet	Goldblatt 1998
Hesperantha coccinea (Backh. & Harv.) Goldblatt & J.C. Manning	*Schizostylis coccinea* Backh. & Harv.	Goldblatt & Manning 1996
Lepidium draba subsp. *draba* L.	*Cardaria draba* (L.) Desv.	Al-Shehbaz *et al.* 2002
Lepidum didymum L.	*Coronopus didymus* (L.) Sm.	Al-Shehbaz *et al.* 2002
Lepidium squamatum Forssk.	*Coronopus squamatus* (Forssk.) Asch.	Al-Shehbaz *et al.* 2002
Nasturtium officinale R.Br.	*Rorippa nasturtiumaquaticum* (L.) Hayek	Al-Shehbaz & Price 1998

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(accepted 2 April 2007)

OBSERVATIONS OF TESTATE AMOEBAE (RHIZOPODA, PROTOZOA) FROM A *SPHAGNUM* BOG IN JACKEYS MARSH, NORTHERN TASMANIA

by David Seamer and Roger Croome

(with one plate, five text-figures and one table)

Seamer, D. G. & Croome, R. L. 2007 (23:xi): Observations of testate amoebae (Rhizopoda, Protozoa) from a *Sphagnum* bog in Jackeys Marsh, northern Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 141(2): 197–202. ISSN 0080-4703. PO Box 92, Moonah, Tasmania 7009, Australia (DS); Department of Environmental Management and Ecology, La Trobe University, PO Box 821, Wodonga, Victoria 3689, Australia (RC*). *Author for correspondence.

Fifty-one species of testate amoebae are reported from surface sediments and sprigs of *Sphagnum cristatum* collected at Jackeys Marsh in northern Tasmania. Included are the rarely observed *Playfairina caudata* and *P. valkanovi*, reported here from Tasmania for the first time. Nine of the observations are new records for Australia.

Key Words: testate amoebae, Rhizopoda, Protozoa, *Sphagnum*, Tasmania.

INTRODUCTION

Freshwater testate amoebae (Rhizopoda, Protozoa) are single-celled organisms, housed within a test or shell which may be organic, or constructed of inorganic materials such as sand and diatom frustules (Ogden & Hedley 1980). Individuals are either herbivorous or carnivorous, and live primarily on the surface of aquatic plants or in the top 2–3 cm of aquatic sediments. Movement is by means of pseudopodia, either fine filopodia or the larger and more tubular lobopodia (pl. 1).

While genetic characterisation has been attempted for individual testate amoebae (e.g., see Wanner *et al.* 1997, Wylezich *et al.* 2002), taxonomic discrimination within the group as a whole is principally by light and electron microscopy, and based largely on the morphology and character of the test.

Australian studies of testate amoebae fall into two time groupings, one from 1885–1923 (von Lendenfeld 1885, 1886, Whitelegge 1891, Hardy 1914, Gillies 1915, 1918, Playfair 1918, Stickland 1919, 1923) and a second from 1993 to date (Bell 1993, Meisterfeld & Tan 1998, Seamer 1998, Shiel & Griggs 1998, Tan 1998). Only Seamer (1998) included material from Tasmania, in his larger work of freshwater protozoa. An earlier listing of testate amoebae from waters within Tasmania's World Heritage Area by Shiel & Tan remains unpublished (see Fulton & Tyler 1993).

In this study we report on some 51 species of testate amoebae from Jackeys Marsh in Tasmania's north, nine of which are new observations for Australia.

METHODS

Several samples of surface sediment and sprigs of *Sphagnum cristatum* Hampe were collected from a shallow bog within Jackeys Marsh (146°40'E, 41°41'S, altitude 480 m) on 3 January 2006. Samples were examined with a Zeiss microscope using a 10x objective under dark-field illumination for initial detection and then high power (40x) with phase contrast for critical measurements and examination of rhizopod tests. The various testate amoebae observed were drawn and measured, and identified using the texts of Playfair (1918), Jung (1942), Ogden & Hedley (1980) and Meisterfeld (2000a, b).

OBSERVATIONS

The "Testates" observed in the Jackeys Marsh samples are listed in table 1, being 24 members of the Order Arcellinida and 27 of the Euglyphida. Numerous specimens were observed of almost half the taxa present (>10, for some >100).

Drawings of a selection of the organisms found are shown in figures 1–5, including nine taxa reported for the first time in Australia.

Cryptodifflugia (fig. 1) – Four species of *Cryptodifflugia* were observed. *C. oviformis* (fig. 1A) was common, *C. compressa* (fig. 1B) was rare, as were two non-compressed and as yet unidentified species (fig. 1C, D).

Corythion, *Sphenoderia* and *Phryganella* (fig. 2) – *Corythion* commonly occurred within the samples, including *C. dubium* (fig. 2A, B). Four species of *Sphenoderia* were observed. *S. macrolepis* (fig. 2C) was the least common of these, with only one test being observed. Two species of *Phryganella* were recorded, with *P. acropodia* (fig. 2D) being frequently observed.

Euglypha (fig. 3) – Fourteen species of *Euglypha* were observed. The common *E. cristata* is pictured (fig. 3A), together with *E. strigosa* (fig. 3B), *E. filifera* (fig. 3C), *E. polylepis* (fig. 3D) and two species which could not be identified (fig. 3E, F).

Trinema and *Playfairina* (fig. 4) – The common *Trinema lineare* is shown as figure 4A, *Playfairina caudata* as figure 4B and *P. valkanovi* as figure 4C. *P. caudata* was originally described from New South Wales by Playfair (1918) as *T. caudatum*: it was renamed by Thomas (1961) from observations in Europe and a report by Jung (1942) from Chile. Meisterfeld & Tan (1998) reported it from Mt Buffalo in Victoria, describing it as an extremely rare species. The observation of *P. caudata* from Jackeys Marsh is thus the third record for Australia, of what must now be regarded as a worldwide but rarely observed species. The single test of *P. caudata* observed was at first considered to be unusual because it lacked an aboral spine, but the authors have since observed several spineless specimens from the highlands of Victoria. The observation of *P. valkanovi* (fig. 4C) is yet more interesting. Described by Golemansky (1966) from material in Bulgaria, it differs from *P. caudata* in size, and in the shape of the posterior of the theca, which is rounded.

TABLE 1
Testate amoebae recorded from *Sphagnum* and sediment samples from Jackeys Marsh, northern Tasmania, 3 January 2006

	Common	Not common	First Australian record
Testacealobosia			
Order Arcellinida			
Suborder Difflugina			
Apodera vas Certes, 1889	x		
Argynnia vitraea v. sphagni Penard, 1911		x	x
Certesella certesi (Penard, 1911)	x		
Certesella martiali Certes, 1889	x		x
Difflugia globulosa Durjadin, 1837	x		
Difflugia lobostoma Leidy, 1874		x	
Difflugia manicata Penard, 1902	x		x
Ellipsopyxella sp.		x	x
Nebela lageniformis Penard, 1890		x	
Nebela militaris Penard, 1890		x	x
Nebela minor Penard, 1902		x	x
Nebela parvula Cash, 1908		x	
Nebela tincta var. *major* Penard, 1902		x	x
Nebela tubulata Brown, 1911	x		
Plagiopyxis sp.		x	
Porosia bigibbosa (Penard, 1890)	x		
Schoenbornia humicola (Schönborn, 1964)		x	x
Trigonopyxis arcula (Leidy, 1879)	x		
Suborder Phryganellina			
Cryptodifflugia compressa Penard, 1890		x	
Cryptodifflugia oviformis Penard, 1890	x		
Cryptodifflugia sp.		x	
Cryptodifflugia sp.		x	
Phryganella acropodia (Hertwig & Lesser, 1874)	x		
Phryganella sp.	x		
Testaceafilosia			
Order Euglyphida			
Assulina muscorum Greeff, 1888	x		
Corythion dubium Taranek, 1881	x		
Corythion sp.	x		
Corythion sp.		x	
Corythion sp.	x		
Euglypha australica Playfair, 1918		x	
Euglypha compressa Carter, 1864	x		
Euglypha compressa var. *obscura* Playfair, 1918		x	
Euglypha cristata Leidy, 1874	x		
Euglypha filifera Penard, 1890		x	
Euglypha laevis Perty, 1849		x	
Euglypha strigosa (Ehrenberg, 1872)	x		
Euglypha sp.		x	
Euglypha sp.		x	
Euglypha sp.		x	
Euglypha sp.		x	
Playfairina caudata (Playfair, 1918)		x	
Playfairina valkanovi Golemansky, 1969		x	
Sphenoderia fissirostris Penard, 1890	x		
Sphenoderia macrolepis Leidy, 1879		x	
Sphenoderia sp.		x	
Sphenoderia sp.	x		
Tracheleuglypha dentata (Vejdovsky, 1882)		x	
Trachelocorythion pulchellum (Penard, 1890)	x		
Trinema complanatum Penard, 1890		x	
Trinema enchelys (Ehrenberg, 1838)	x		
Trinema lineare Penard, 1890	x		

PLATE 1
Photomicrograph of live specimen of Apodera vas, *showing tubular lobopodia.*

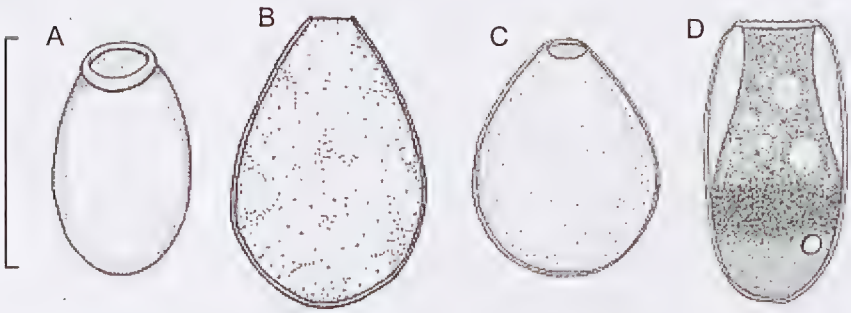

FIG. 1 — Cryptodifflugia. *(A)* C. oviformis. *(B)* C. compressa. *(C, D) Unknown species. Scale bar 25 µm.*

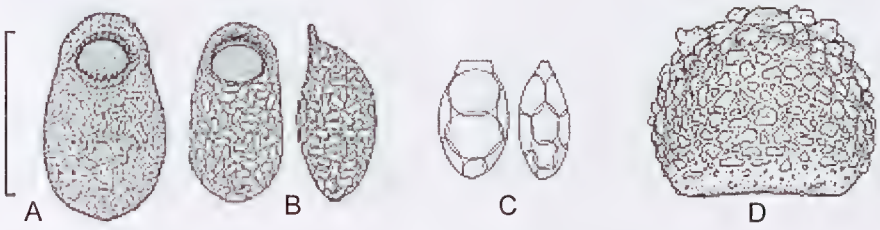

FIG. 2 — (A, B) Corythion dubium. (C) Sphenoderia macrolepis. (D) Phryganella acropodia. Scale bar 50 µm.

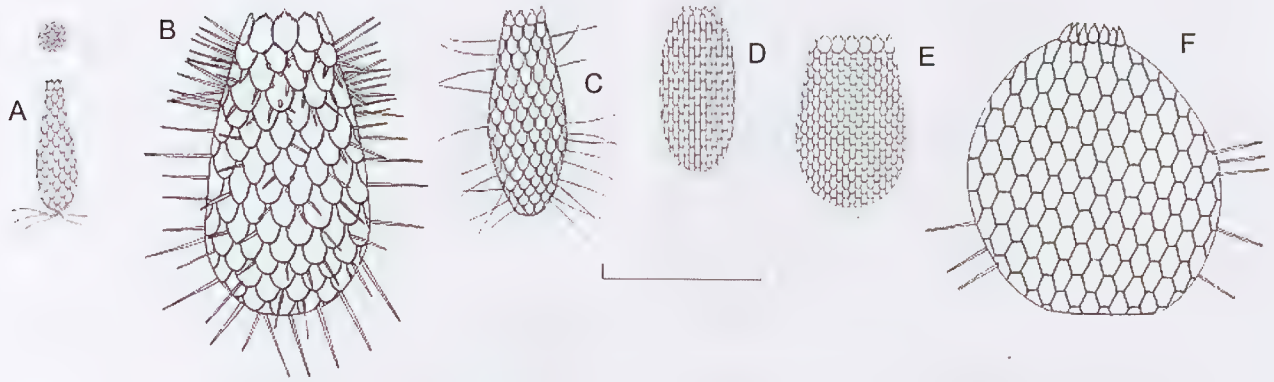

FIG. 3 — Euglypha. *(A)* E. cristata. *(B)* E. strigosa. *(C)* E. filifera. *(D)* E. polylepis. *(E, F) Unknown species. Scale bar 50 µm.*

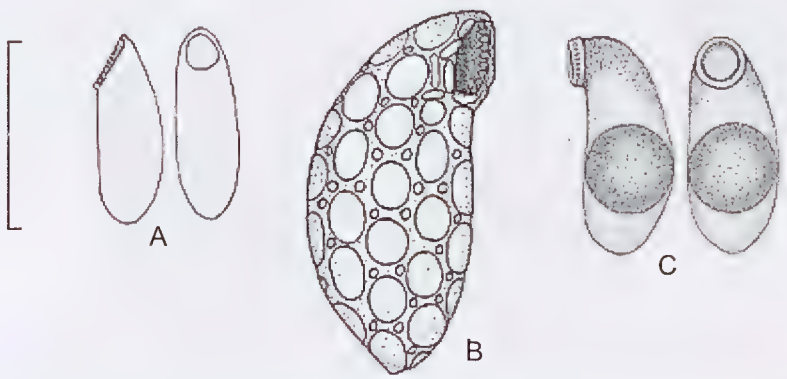

FIG. 4 — Trinema *and* Playfairina. *(A)* Trinema lineare. *(B)* Playfairina caudata. *(C)* P. valkanovi. *Scale bar 25 µm.*

Rarely sighted worldwide, it has been reported from Mt Buffalo in Victoria by Meisterfeld & Tan (1998), and now here in Tasmania.

First observations for Australia

The nine taxa observed for the first time in Australia are shown in figure 5. These are:

Nebela minor (fig. 5A). Test flask-shaped and transparent, with predated eugyphal plates attached. Aperture elliptical and slightly arched, with a distinct organic rim. Length of test 95 μm, width 62 μm, aperture 20 μm. Numerous specimens observed.

Nebela tincta var. *major* (fig. 5B). Test ovoid and with rough surface, flattened, with sides tapering gradually towards the apex. Semi-transparent, with two lateral pores and numerous predated euglyphal plates. Aperture wide and elliptical, surrounded by a rim. Length 112 μm, width 70 μm, aperture 32 μm. Only one specimen observed.

Nebela militaris (fig. 5C). Laterally flattened, ovoid/elongate with a gradually tapering neck. Test elliptical in cross-section, with two lateral pores. Aperture oval, surrounded by a rim. Length 70 μm, width 35 μm, aperture 16 μm. Only one specimen observed.

Nebela parvula (fig. 5D). Test transparent, laterally flattened, ovoid, tapering towards a relatively large and elliptical aperture, surrounded by a rim. Oval in cross-section, with two lateral pores. Length 80 μm, width 60 μm, aperture 20 μm. Three specimens observed.

Difflugia manicata (fig. 5E). Test broadly ovoid, round in cross section, and with rounded posterior. Surface covered with numerous mineral particles. Large circular aperture. Length 80 μm, width 55 μm, aperture 25 μm. Numerous specimens observed.

Certesella martiali (fig. 5F). Test-flask shaped, with two pores within depressions at the base of the neck, and two grooves between multiple rows of teeth at the anterior end. Aperture oval, slightly arched, surrounded by a definite organic rim. Length 145–175 μm, width 75–100 μm, aperture 36–42 μm. Numerous specimens observed.

Schoenbornia sp. (fig. 5G). Test ovate, circular in cross section and covered by both mineral particles and predated euglyphal plates. Aperture circular with a smooth border. Length 50 μm, width 35μm, aperture 12 μm. Only one specimen observed. First observation of the genus from Australia.

Argynnia vitraea v. *sphagni* (fig. 5H). Test laterally compressed, ovate with rounded sides converging towards a well-defined aperture. Aperture oval-elongate with a rough

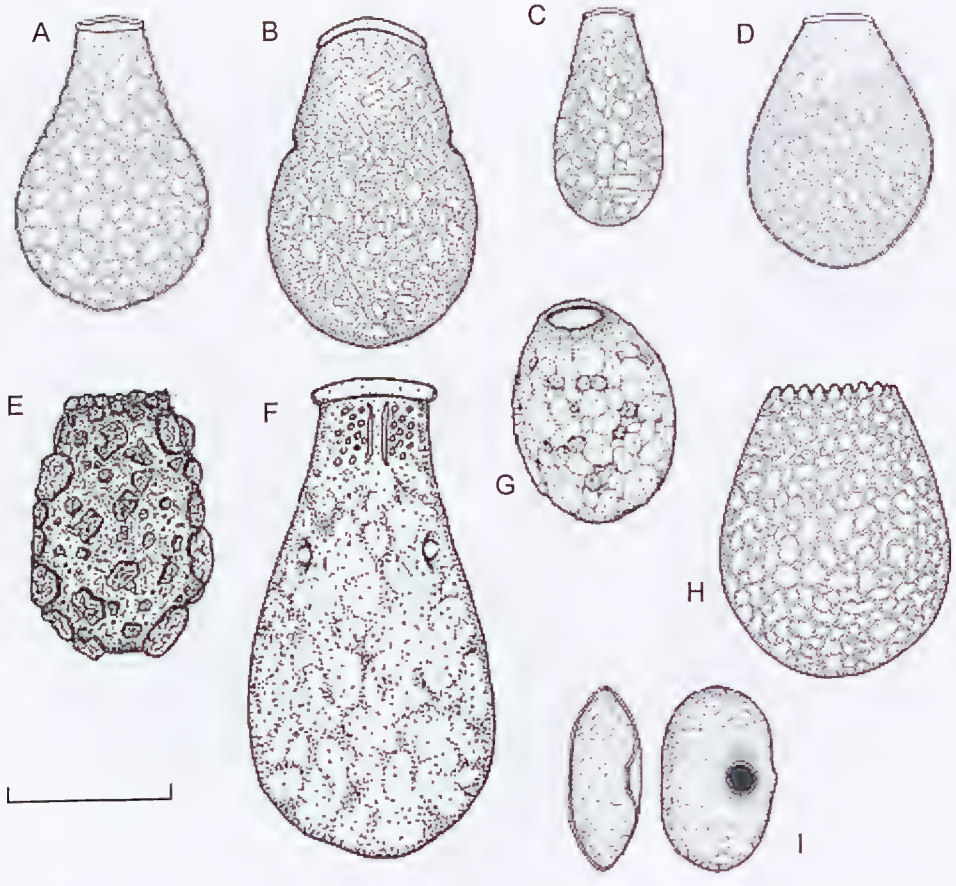

FIG. 5 — First observations for Australia. (A) Nebela minor. *(B)* Nebela tincta *var.* major. *(C)* Nebela militaris. *(D)* Nebela parvula. *(E)* Difflugia manicata. *(F)* Certesella martiali. *(G)* Schoenbornia *sp. (H)* Argynnia vitraea *var.* sphagni. *(I)* Ellipsopyxella *sp. Scale bar 50 μm.*

outline and rimmed with small mineral scales. Length 95 μm, width 75 μm, aperture 25 μm. Numerous specimens observed but not common.

Ellipsopyxella sp. (fig. 5i). Test yellowish, squarely-ovoid in dorsal view, pointedly-oval in lateral view. Transparent, with a slight bulge near the aperture in dorsal view. Aperture off-centre, evaginated, circular and located within a depression. Length 55 μm, width 35 μm, depth 20 μm, aperture 10 μm. Only one specimen observed. First observation of the genus from Australia.

The 51 organisms reported here from Jackeys Marsh are undoubtedly only a portion of the testate amoebae present throughout Tasmania. This makes the recording of nine taxa for the first time in Australia, two at genus level (*Ellipsopyxella* and *Schoenbornia*), even more significant. Future observations can only improve our knowledge of these cryptic organisms, and are to be encouraged.

Circumstances prevented the collection of water quality data within this study, which elsewhere in the world has shown a relationship between the occurrence and diversity of testate amoebae and the availability of water, and the effect, once sufficient water is present, of increased nutrient and dissolved organic carbon concentrations (Tolonen *et al.* 1994). Future Australian studies of testate amoebae should include as much as possible the collection of relevant water quality data.

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(accepted 27 February 2007)

GEORG NEUMAYER (1826–1909) IN TASMANIA, 1864

by Patrick G. Quilty

(with three plates)

Quilty, P. G. (23:xi): Georg Neumayer (1826–1909) in Tasmania, 1864. *Papers and Proceedings of the Royal Society of Tasmania* 141(2): 203–212. ISSN 0080-4703. School of Earth Sciences, University of Tasmania, Private Bag 79, Hobart, Tasmania 7001, Australia. Email: P.Quilty@utas.edu.au

It is now clear that Georg [von] Neumayer (enobled after this time) spent time in Tasmania between 8 and 19 April 1864. He was near the end of his five-year sojourn in Victoria where he conducted a major geomagnetic study of Victoria and established the Flagstaff Observatory on the site of the current Flagstaff Gardens. His visit to Tasmania was to re-measure the magnetic parameters first documented by members of the 1840/41 James Clark Ross expedition at Rossbank Observatory on the grounds of present-day Tasmanian Government House, shortly prior to its construction. This paper contains a translation of a 1905 German account of his visit to Tasmania and contains the results of his magnetic studies here, including details of the instruments used. It also includes reference to a Tasmanian (Launceston) media report of a presentation to the Melbourne Chamber of Commerce.

Key Words: Neumayer, geomagnetism, Rossbank Observatory, Flagstaff Observatory, Tasmania.

INTRODUCTION

While never venturing there himself, Georg von Neumayer (pl. 1), a totally dedicated scientist, was in the background of every major German expedition to the Antarctic and sub-Antarctic in the mid-nineteenth and early twentieth centuries, and was actively involved in all the discussions prior to the Heroic Era of Antarctic exploration in the early 1900s. He had hoped to venture to Antarctica in about 1870, but the outbreak of war between Germany and Austria prevented that. He was an organiser of the Indian Ocean explorations of the *Arkona* and *Gazelle*, both in support of identifying a location to observe the December 1874 Transit of Venus; he was behind the establishment of a German observatory on South Georgia for the first International Polar Year (IPY, 1882/1883), and a major proponent of the IPY. Neumayer later was an instigator of the *Gauss* expedition of 1901–1903 (Drygalski 1904) to the southern Indian Ocean. The German Antarctic station Neumayer is named in his honour. Roald Amundsen, another explorer associated with Tasmania, stated that, in von Neumayer, Antarctic research never had a "...warmer, nobler, and more high-minded champion. So long as 'Antarctica' endures, the name of Neumayer will always be connected with it" (Amundsen 1912, p. 16).

Neumayer's interests lay in exploration *per se* and physical sciences such as meteorology and oceanography. But he was particularly interested in gaining an understanding of terrestrial magnetism, and it is through this pursuit that he is sometimes quoted as having come to Tasmania – although this is also sometimes denied. His experience and influence in Australia are summarised in Home (1990, 1995, 2005), Home & Kretzer (1991) and Morrison (2006). While Morrison (2006) refers to the Hobart excursion, no one has addressed adequately Neumayer's short sojourn in Tasmania. Lefroy (1882) referred to the magnetic measurements taken during his time in Tasmania.

This paper provides a summary of the Tasmanian associations of Georg Neumayer, including a translation of his (1905) paper documenting his sojourn in Tasmania recording magnetic data, and also includes a record of a presentation made to the Melbourne Chamber of Commerce as reported in the Tasmanian media.

PLATE 1

Georg Neumayer in 1872, some eight years after his visit to Tasmania (reproduced with permission from Prof. R. Krause, Alfred-Wegener-Institutes für Polar- und Meeresforschung, Bremerhaven).

Georg Balthasar Neumayer was born on 21 June 1826, in Kirchheimbolanden, Germany. He studied science at

Munich, and it is commonly stated that he received a doctorate in 1851; however, Home & Kretzer (1991) note that the doctorate was achieved after his return to Germany from Australia. Unable or unwilling to get immediate employment as a physicist, he went to sea as a seaman to Brazil and Australia, and later took a mate's ticket and trained in navigation and astronomy. He took up a chair in physics in Hamburg but in 1852, sailed for Australia, arriving in Sydney on 5 August. Here he participated in a variety of tasks such as gold mining at Bendigo (two months), and sailed around the coast of Victoria. It is sometimes stated that he visited Tasmania during this time (for example in 1852 or 1853, McGregor *et al.* 1985) to conduct research in Hobart on data from the Rossbank Observatory (McGregor *et al.* 1985, Savours & McConnell 1982, 1997). The observatory had been built by James Clark Ross in the grounds of the current Government House in Hobart during Ross' visit in 1840/41 as part of a global Magnetic Crusade (Cawood 1979). However, there is no evidence to support this contention and the lack of any reference to it in Neumayer's own writing suggests that his only visit was later. After his brief sojourn in Australia, he returned to Bavaria in 1854 where he received support from Alexander von Humboldt for establishment of the Flagstaff Observatory for Geophysics, Magnetism and Nautical Science in Flagstaff Gardens, Melbourne, obtained some funding from King Maximilian II, and returned in 1857 as the observatory's director. Other funds came from the Victorian government and German settlers in Victoria. He was also involved in the choice of the subsequent observatory site near the Melbourne Botanical Gardens. Towards the end of his sojourn at the Flagstaff Observatory (1858–1864), Neumayer sailed to Tasmania and spent 8–19 April 1864 working here, initially to take magnetic observations in Launceston and, later, in-depth observations in Hobart.

Neumayer arrived in Launceston on 8 April 1864 but could determine only the horizontal component of the Earth's magnetic field at that site. On 9 April, he travelled the 121 statute miles to Hobart by "Cobbs Coach", making complimentary comments on what he saw on the trip, noting particularly the abundance of public houses to offer the traveller refreshments for the dusty journey. He arrived in Hobart before sunset and was met by the Consul of Hanover, a Mr Ernst Marwedel. The following morning (10 April), he familiarised himself with the local geography and contacted the astronomer and manufacturer of chronometers, Mr Francis Abbot (1799–1883, Rimmer 1969), who helped with timekeeping, and who also could remember details of the conditions at the time of foundation of the Rossbank Observatory. The next day (11 April) was spent checking and maintaining his instruments. He also visited the site of the Rossbank Observatory accompanied by geologist Charles Gould (1834–1893) whose formal title was Geological Surveyor. He was the son of John Gould (1804–1881), the ornithologist. On 12 April, Neumayer set up his instruments close (200 m) to the site of the former observatory and a few metres from the quarry that was the source of some of the sandstone for the current Government House. He was careful to ensure that the site gave him a clear view of the skies so he could determine orientation of geographic reference points by reference to the sun and stars. Unfortunately, the weather that day was not favourable. He noted that the coordinates of the original observatory were 42°52'48" S; 147°26'30" E. He even kept a record of the chronometers he used for his observations. It seems 13 April was another day of overcast skies. He departed Hobart by ship on 19 April arriving in Melbourne a day and a half later, commenting on the picturesque east coast of Tasmania with its "basalt" (dolerite) columns. In Melbourne he re-calibrated his instruments and tidied up the results before departing Australia for Europe on 21 June 1864. His experience in Australia persuaded him that it was an ideal site for the study of terrestrial magnetism. He also had a longer-term ambition to study Antarctic magnetism because he believed that magnetic phenomena could not be understood properly without study in the Antarctic.

He notes in the paper that he submitted a report in English to the President of the Royal Society "....which, however, as far as I know, was never published". This observation is correct as the work was not published.

Neumayer returned to Europe in 1864 where he eventually became director of the Hydrographic Office in Hamburg, from 1876–1903. In this role he was one of the major influences in later expeditions to the Antarctic, partly through his role as Chairman of the International Polar Year Commission. He was subsequently ennobled as *von Neumayer* by the King of Bavaria and it was as von Neumayer that he published the account of his sojourn in Tasmania in 1905. He died on 24 May 1909 in Neustadt.

General comments he made referred to the desirability of keeping the magnetic observatory in Hobart operational continuously. This arose because it had closed in 1854. He also commented on the unsuitability of the sites of magnetic observations because of the influence of "great basalt masses" (mainly the widespread Jurassic dolerite).

McAulay & Hogg (1902) summarised the history of magnetic studies in Tasmania but refer to Neumayer's visit as having been in 1863. McGregor *et al.* (1985) referred to the visit of Neumayer in 1864 and stated that while Neumayer was careful to avoid the influence of the dolerite, his value for D (declination or difference between true north and magnetic north) was about 0.5° too high. Fenton (2005) also mentioned the 1864 visit by Neumayer.

MAGNETIC OBSERVATIONS

The following is a translation of von Neumayer (1905).

Some comments on the translation which follows:

Wording: A few expressions have been altered slightly to make the translation more readable.

Format: Paragraphs and indentations follow the original.

Nomenclature: Geographic nomenclature is as used by Neumayer. Thus Hobarton, Rumeney Hill (now Mt Rumney). In some cases, [...] are used for clarification or amplification. The chimney (pl.2) used as a reference point was of a smelter at Rosny on the eastern shore of the Derwent River.

'Cobbs coach': Von Neumayer refers to travel by "Cobbs coach". Cobb and Co. never operated in Tasmania and his reference in inverted commas clearly means he understood that he was not travelling by Cobb and Co. but in a coach of the style used by Cobb and Co. He travelled "sitting on the Imperial" which is the "roof seat of a coach, omnibus or railway car" (Berkebile 1979).

Tasmania's population: Von Neumayer states that Tasmania's population in 1864 was 19 400. It was a little over 90 000. Perhaps his estimate relates to the population of Hobart.

Rock formations: Von Neumayer refers to Gould's advice on the age of the sandstone as Silurian (approximately 420 million years) or Palaeozoic (545–251 million years). The age

PLATE 2
1894 sketch by T.W. Midwood of the foundry chimney at Rosny used as a survey reference point. Reproduced with permission from the Heritage Collections of the State Library of Tasmania.

is actually considerably younger as Triassic (251–205 million years). For basalt in so many citations, read dolerite which is Jurassic (approximately 180 million years).
Units: Units are as used by von Neumayer.
Beach[?]: The word *Strand* is used in three places. Its meaning is unclear and it is recorded here as beach[?].
G E is Gaußsche Einhiet = Gaussian Unit = 10 000 nT (nannotesla) in modern terms.
E E is Britische Einheit = British Unit = 4610.8 nT.
Footnotes: The original contains a series of 15 footnotes numbered sequentially from 1 for each page. Here they are numbered sequentially for the entire paper and included at the end. Several were given in English and are designated as original where relevant.
Rossbank Observatory: Von Neumayer states that the observatory closed in 1848 but it was not closed until 31 December 1854. Home & Kretzer (1991) quote another statement by von Neumayer in 1901 that it closed in 1849.

THE GEO-MAGNETIC CONDITIONS OF THE FORMER EARTH-MAGNETIC OBSERVATORY IN HOBARTON (TASMANIA)

by Dr G. von Neumayer

It is probably common knowledge that in conjunction with the epoch-making English expedition to the South Pole by Sir James Clark Ross (1839–1843), an earth magnetic observatory was erected in Hobarton in Tasmania in order to serve as a base for observations in the far south. Occasioned to a large degree by the magnetic studies of Karl Friedrich Gauss, the astronomer from Göttingen, and supported by the authority of Alexander von Humboldt, a number of such observatories were erected in the British colonies and kept for observation for a longer period. In addition to that in Hobarton I just want to mention the observatories in Cape Town, on St. Helena and in Toronto, the Dominion of Canada. Occasioned and directed by the later president of the Royal Society in London, Sir Edward Sabine, the results of these observatories, kept on average for eight to ten years, were gathered and also published comprehensively in handsome volumes as were the observations from Hobarton.[1] Most of these observatories have become of considerable importance because of their discussion in the Transactions of the Royal Society and serve as a base for the modern approach to geomagnetic research. In a quite comprehensive way, parts of the results have been published by [Edward] Walker [1865] in a highly regarded paper "*Cosmic and Terrestrial Magnetism*"; there are also numerous articles in the Royal Society in London. The observatories under discussion, as those of Hobarton, were unfortunately discontinued after a period which, according to the views then current, was sufficient. Today, more than 50 years later, geomagnetic researchers no longer believe that after such a limited time, everything necessary for understanding geomagnetism has been recorded; on the contrary one is now of the opinion, that with all due respect, that the results of the researchers of half a century ago could benefit from the results from these famous observatories and are now convinced that we need many more years of observation in numerous observatories, strategically placed all over the globe, in order to obtain data to continue and expand successfully the initial research. Now, whoever looks at the observatories, which in all parts of the earth have recorded millions of observations, can hardly believe in an earlier time, when leading intellectuals in the sciences viewed the results from these institutes as sufficient and, in a sense, as complete. In the place of those perhaps half a dozen geomagnetic observatories which owe their existence to British scientific curiosity and expense, there are today hundreds kept by various nations, equipped with the latest instruments. Today's discerning researcher cannot assume that the end of the research epoch has been reached or is even near, and the writer states that he was one of the first to oppose the opinion that by the time the observatories in the British colonies were terminated, enough observations existed to arrive at a theory of geomagnetic phenomena. He regrets especially that the observatory in the deep south at Hobarton is no longer in operation and, in two memoranda, one directed to Alexander von Humboldt, the other to King Maximilian II of Bavaria, supported by von Liebig, then president of the Royal Academy of Science in Munich, argues the necessity of re-establishing the work of Hobarton, which closed in 1848, and re-open and continue it with

improved equipment and methods. Petitions were presented in December 1854 to June of the following year. That one concerned oneself with continuation of the activities of the observatory of Hobarton – but at a different location in the Australian colonies – and not recommended the continuation of the other observatories has its reasons in that the writer 1. was convinced by his geomagnetic studies of the scientific necessity for the re-opening of magnetic observatories and 2. because of his experience of several years in the Australian colonies he believed that because of the discovery of gold (1852), the great development of the colonies would provide likely financial support for scientific endeavour. It is obvious to everyone who knows the conditions in these states that it is not advisable to return to Hobarton, because the colony of Tasmania is, in contrast to the blossoming colonies on the mainland, less developed and during 1864 only had about 19 400 inhabitants. It is reliant on its own resources. So the re-opening of the Hobarton-observatory was not recommended; however it was shown that a geomagnetic observatory in Melbourne, also in the far south could fill this gap. The success of this decision is obvious from the works of the writer, and is underscored by the further fact that, linked to his work, an observatory for geomagnetic purposes has been operated continuously for almost 45 years and publishes its observations. However, nobody who has enough knowledge of geomagnetic research believes that we are closer to an end to a research era, and such a person will most eagerly wish that another period of stagnancy and interruption does not follow.

.. The writer stresses this point in order to underline the fact that it was not easy for him to fight against existing prejudices to secure success for his conviction in a deliberate way. To fight against deeply ingrained views which rest on certain experiences and have been shared even by scientists has at all times been a barrier to the advancement of science and is also quite difficult in this case.

The observatory in Melbourne was first erected provisionally on a spot not really suitable from a geological point of view but was maintained there for several years. Because of the experience gained in the meantime, particularly an understanding of magnetic features of the geological formations around Melbourne, a suitable site[2] for a geomagnetic observatory was found, one was built, and it still is there. The Silurian formation, which predominates at the site of the observatory, has proved quite suitable so far.

As is known, I carried out a geomagnetic survey of Victoria during the years 1858 to 1864 with the observatory in Melbourne as base.

After completing the task assigned to me (the installation of a geomagnetic observatory in Melbourne and the geomagnetic survey of Victoria) I prepared to return to Europe. When Sir Edward Sabine learned of my impending return to Europe, he asked me at the beginning of 1864, before leaving Australia, to visit the site of the observatory of the years 1841–1848 in Hobarton and to determine the magnetic elements, so that a connection could be made from my observations on the Australian mainland to the former observatory in Hobarton. It would also be useful to determine the changes in the magnetic elements that had occurred in that time. I gladly agreed to his wishes because I too had an interest in connecting the observatory in Melbourne to the one in Hobarton. This is why I decided to travel to Tasmania. In April 1864 I began the journey, made magnetic observations in Launceston, the most northerly city on the island and made in-depth observations in Hobarton and its surroundings from 12–19 April 1864. After my return to Europe I sent a detailed report in English to the president of the Royal Society in London, which however, as far as I know, was never published. In my "Discussions"[3] I only briefly mentioned the result of this investigation, but in my work on the geomagnetic survey of Victoria[4], p. 196, I gave a short report about the geomagnetic measurement results and related secular changes of the magnetic elements in the year 1864.

With this situation and the high interest that is still evident about the observations in Hobarton, it seems appropriate to give the following account of my former observations. In it I will, after discussing the observations in details, repeat some of the above-mentioned report from the year 1867.

Before leaving Melbourne the constants of Lamont's geomagnetic survey theodolite were determined thoroughly, after the magnetic elements for the observatory in Melbourne had been derived. Of particular interest was the determination of the value of the constant of the differential inclinometer with "soft" magnetic iron rods, and this was even more important because a dip needle could not be taken on the journey, as it would surely have been damaged on the journey through Tasmania, which had to be undertaken by "Cobbs-Coach".

I can also mention that after returning to Melbourne from Tasmania, the constants of the instrument were calibrated with the same care in the Melbourne observatory between 17 March and 17 June 1864. The latter was particularly relevant to the differential inclinometer.

On the journey on the steamer from Melbourne to Launceston (latitude 41°30' S; longitude 147°14' E) we had beautiful weather but heavy seas. Immediately after embarking in Launceston on 8 April, I started a series of observations in the afternoon. To my regret it was too late to carry out any azimuth determination of a distant object for magnetic declination measurements. I therefore limited myself to determination of the horizontal intensity with both magnets and the inclination with the differential inclinometer. Throughout the journey I was very careful to keep the constants of the magnets unchanged because only in Hobarton could the intensity be determined from oscillation and deflection observations. Here I give the result of magnetic inclination determination, because it is of special interest for the readings in Hobarton. On the mentioned day between 4.57 and 5.46 in the afternoon the inclination was 70°04.65' S. Later in the report I will mention that the geological formation is very inappropriate for magnetic observation, because here, as almost everywhere on the east coast of Tasmania, the great basalt masses [Jurassic dolerite] may influence the magnetic elements to a great degree.

On the following day, 9th April, I travelled in most beautiful weather sitting on the Imperial of 'Cobbs-Coach' through the beautiful landscape of the 121 Statute Miles distance to Hobarton. While in the eastern parts of Tasmania, through which the road travels, the land is agricultural, the western part is very mountainous, picturesque and mainly pastoral. The few villages through which the road travels show beginnings of cultural life and one hopes that these areas, supported by generous assistance, have blossomed since then. Even then there were everywhere along the road plenty of "Public-Houses" to offer the traveller refreshments from the dusty journey. Close to evening we approached the capital of the island situated beautifully on the Derwent and the number of settlements consisting sometimes of quite nice

houses, increased. Before sunset we reached Hobarton where I was welcomed most heartily by the Consul of Hanover Mr Ernst Marwedel, whom I know from my home.

I used the following morning to inform myself with the aid of city maps on general conditions, also in particular the site and surroundings of the former, now so famous, magnetic observatory.

To this end I contacted the honourable astronomer Mr F. Abbott, F.R.A.S., a maker of chronometers. For many years Mr Abbott has made meteorological observations and in particular made a name for himself for navigational conditions on the Derwent by determining time; this worthy man was then already aged and could remember details of the conditions at the time of the establishment of the observatory by Sir James Cl. Ross and I thank him for the most thorough information about the conditions in question. After I had checked all instruments and conducted maintenance on them on 11 April, Mr Abbott invited me to inspect the surroundings of the government building and I accepted the invitation with thanks. The young geologist [Charles] Gould, a son of the famous ornithologist [John] Gould in London, informed me about the geological conditions of the surroundings, something that I appreciated very much. It is however my duty to explain that Mr Gould gave me his data under the proviso that the geological examination was too recent to say with complete certainty the character and age of the formations. Finally, on the morning of 12th April I could set up the instruments close to the former observatory for observations. Since I decided on this spot (A on the attached plan) [pl. 3; fig. 9 in the original] to conduct a longer series of observations, I was careful to ram the tripod into the soil so that it would stay that way for several days. When erecting it, I was particularly conscious to keep the view free towards the heavens, so that I could determine the azimuth of reference points by way of observing the sun or stars alone; I had no geodetically determined points for that purpose at my disposal. To begin with I set up close to a battery. From this station I could intersect several points in the distance, among them also some trigonometric stations (the coordinates were not known to me); however the weather was not favourable for astronomical observations on this day, but it was favourable for magnetic observations because the sky was covered and there was virtually no wind. For the mentioned point A,

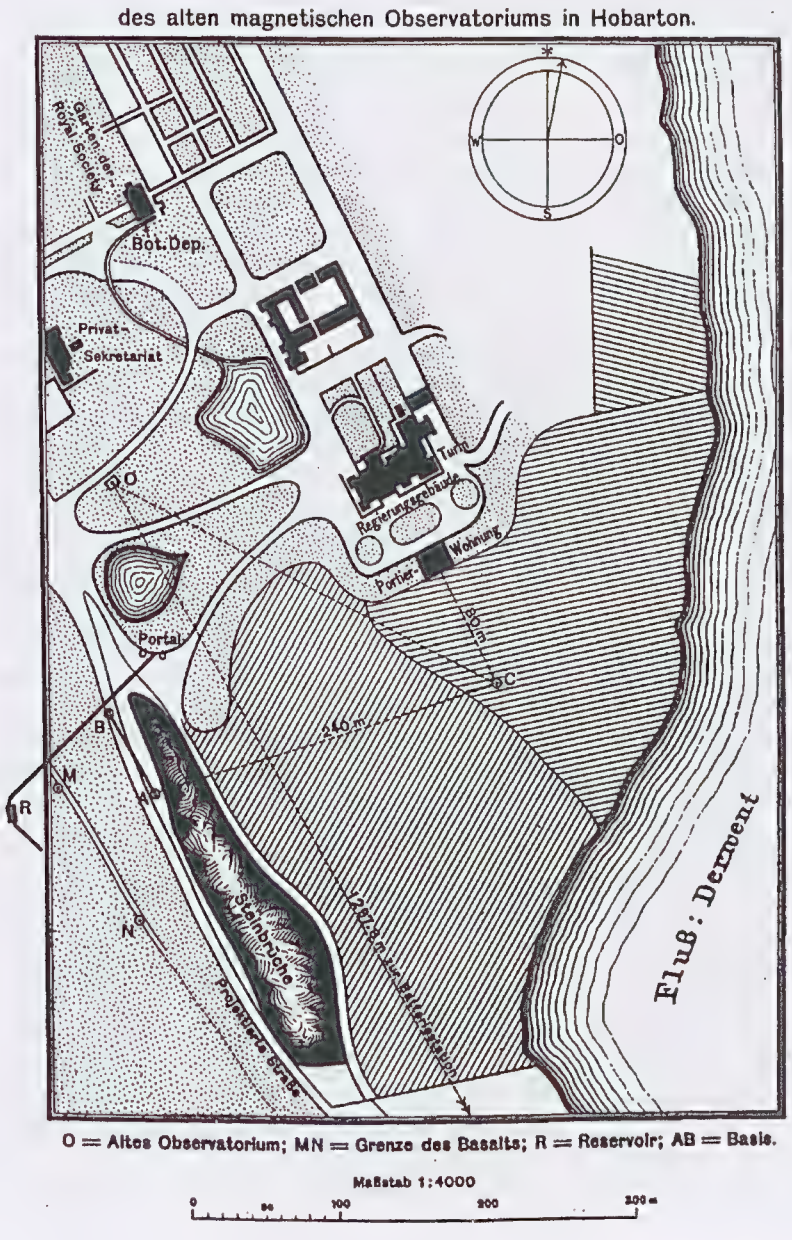

PLATE 3

(Fig. 9 in the original) Map showing the Government House site of the re-measurement of magnetic parameters. As published in the original. O is the site of the original Rossbank Observatory; A, B and C are the survey points mentioned in the text. R is the reservoir.

where I made most of the observations, I determined the geographical coordinates from the site of the old observatory as follows:
Latitude 42°52"48' S;
Longitude 147°26"30' E (9 hr 49 m 46 sec)

To determine the errors of my watches, a golden English Anker watch No. 3354 and a silver watch with duplex-escapement of French construction, I was supported during the overcast days by Mr Abbott in the most friendly way, until on the morning of 14th April I could determine the errors of the watches myself.

On the following plan of the surroundings of the former observatory and Government House, all those points which are of importance for the measurements, are marked and all that is necessary for the understanding is obvious.

At all the following points, observations were made.

1. Point A has been chosen with particular care because it is an end point of a base line for a small area observation. This point was about 200 m from the old geomagnetic observatory. The direction of this point was about S 4°28' W from the observatory. It was a few metres from the western rim of a quarry, from which sandstone has been taken for the building of Government House, and on the western side of a proposed new road.

2. Point B, the other end point of the base line, was situated about 143 m from the old observatory, almost exactly south of it and on the other side of the proposed new road. It was 58 m N 30°40.7' W from point A; the base for data collecting had thus the given length.

3. Point C, about 280m S 63° E of the old observatory[5] was about 240 m N 70°52.8' E from point A and 80 m S 25°30' E from the caretaker's cottage of the government building. The area sloped down from the caretaker's cottage towards the southeast, so that this point was about 6 m below the building. The land was under agriculture and I was told the geological formation was Silurian or Palaeozoic to a rather considerable extent. Point C was about 105 m from the western banks of the River Derwent.

4. A point, called Battery Point (I described it above) which was situated entirely on basalt was S 30° E about 1300 m from the old geomagnetic observatory.

5. The old magnetic observatory, in the immediate vicinity of which one could at the time no longer conduct geomagnetic observations because of gas and water pipes, was situated on a small strip of probably Silurian sandstone within the so called "Government Reserve" about SSE 190 m (middle of the government building).

It is assumed that this observatory was established by Sir James Cl. Ross with all due care in such a way that large local disturbances could be considered eliminated. How this relates to the overall situation in geological terms will be obvious from the following details of the report.

Observations of which results are given, were taken at the points mentioned, although a detailed description of the original observation is omitted.

At Battery-Point (point 4), on 12th April, magnetic observations were carried out for horizontal intensity and inclination. The reference points were the peak of Mt Wellington, a trigonometric signal on Mt Rumeney, the tower of Government House and a church tower in Hobarton.

The value of the horizontal intensity was:

H = 1.9965 G E,

the magnetic inclination:

J = 72°2.57'S.

The inclination was, as mentioned in the introduction, referred by means of the differential inclinometer to the observatory in Melbourne.

Point A. As remarked in the introduction, at this point the tripod was rammed into the soil in such a way that it stayed undisturbed[6] over several days.

Reference points were:

Trigonometric station on Mt. Rumeney	N 84°30.23' E
Tower of Government House	N 43°36.47' E
Chimney of a foundry	N 74°56.88' E

Magnetic intensity was measured on 13th April with two magnets and at four different deviation observation series in the afternoon from12.39–2.40; magnetic inclination was observed by means of the differential inclinometer from 3.01 to 4.45. The weather was stormy and with strong gusty wind from the northwest; towards evening there were several rain showers. Therefore neither astronomical determinations nor oscillation observations could be carried out. In order to determine the intensity, both magnets in eight series of deviations were used, while the inclination observations were taken with the differential inclinometer. The results were:

Horizontal intensity	H = 2.0506 G E
Inclination	J = 70°47.93' S
Declination	D = 10°22.33' E[7]

On 14th April. From 10.55 in the morning until 12.50 in the afternoon an absolute determination of the magnetic declination was taken. All observations were referred to the variation instruments in Melbourne. The declination magnet was observed in two different positions in order to eliminate collimation error. The average of both positions was calculated as 50°1.62', if reduced to Melbourne. The collimation error of the mirror was determined as 16.0'. The torsion of the thread was determined as 3.80' by means of the torsion and the declination magnet, from which the magnetic meridian for 76.1 of the Melbourne scale was determined to be 50°15.82'.

In the afternoon of the 14th after the declination observations, determinations of time were carried out using the top rim of the moon and the error of golden watch 3354 calculated from four different series and determined to be 2 m 33 s behind the Hobarton mean time. Following that, from observations of the upper rim of the sun the collimation error of the circle and the following azimuths were determined:

The chimney	N74°56.88'E
Trigonometric station Rumeney Hill	N84°30.23'E
Tower of Government House	N43°36.47'E

Then, with the survey theodolite, which, as mentioned did not have a reversible needle, the magnetic intensity was observed with magnet 1 in eight deviation series.

Even though the weather was favourable on that day, oscillation and inclination determinations could not be carried out; however in the evening determination of the azimuth was carried out by using observations of the centre point of the sun. These corresponded exactly with the previous results. The results of these observations were for the magnetic declination on the base of the meridian which was found above by means of the reversible needle as 50°15.82' and the measured collimation error of the circle

D = 10°25.98'E (for the middle of the day)

for the horizontal intensity

H = 2.05127 G E.

On 15th April the weather was very beautiful and there was a light northeasterly breeze, so that it was possible to get oscillation observations for intensity determinations. Mr Abbott was so kind as to lend me a chronometer for this purpose. After the torsion of the thread was carefully compensated for, two complete oscillation series were conducted with magnet 2 (according to Lamont's directions, six complete series); the same happened with magnet 1 and the observations carried out between 8.57 and 10.24 in the morning were completed very well. Soon after the observation, a rather strong breeze started from NW bringing threatening weather, but in spite of this the necessary deviations of both magnets could be carried out and were combined with the oscillations in order to determine horizontal intensity. The deviation observations started at 10.01 and concluded at 11.30 in the morning. A comparison of the watches resulted in:

Golden watch 3354	0 h 01 m 15 s behind Hobart time
Duplex	0 h 10 m 06 s "
Chronometer Rochell	0 h 00 m 44 s ahead of "

From the deviation observations it was deduced to be a somewhat unstable torsion:

The magnetic declination to D = 10°26.98' E[8]

The average of all observations of magnetic horizontal intensity is:

H = 2.05127 G E.

On 16th April, next day. The magnetic theodolite was set up exactly in the former position and I immediately started determining time by measurement of the height of the lower rim of the sun in both positions of the reflection circle. The observation took place between 9.20 and 9.42 in the morning. Arranged into three different series and calculated, the error of the golden watch on average was determined to be 1 m 35 s behind the mean time of Hobart. Then the distance of the distant sun rim to the tip of the chimney of the foundry was measured with the reflection circle in different series, the resulting azimuth of the chimney was N75°27.77' E, of which, because the reading of the reference mark chimney was N255°45.72' E, the northern point of the theodolite was determined as 331°13.49', other reference points and their azimuths were:

Trigonometric Station on Rumeney Hill	N85°0.54' E
Hobarton Observatory	N4°27.76' W
Station B[9]	N30°14.71' W
Tower of Government House	N44°6.04' E
Station C	N70°52.79' E

The value of the magnetic declination was:

D= 10°24.04' E

and the magnetic inclination

J = 70°47.36' S

(see further below).

On 19th April the theodolite was set up at Station C on a slope. The distance from station A was 235 m in direction N 70°56.13' E and from the caretaker's house 80m, as mentioned above. It can be seen that station C, although situated still on a Silurian area, is coming close to basaltic formations. The magnetic elements were:

Horizontal intensity	H = 2.0177 G E
Inclination	J = 71°18.12' S
Declination	D = 9°51.33' E

It has to be said subsequently that on 16th April the theodolite was also set up on the other end of the short baseline at station B.

These were the resulting azimuths:

Station A	S30°40.76' E
Observatory in Hobarton	N5°3.50' E
Chimney of the foundry	N76°31.1' E
Tower of Government House	N56°32.5' E
Entry to the Park (Government P.)	N37°53.0' E

The magnetic elements were:

Magnetic Declination	D = 10°47.32' E
Magnetic horizontal intensity	H = 2.0702 G E

It needs to be mentioned here in particular, that the observations were conducted under quite favourable weather conditions; other disturbances were also not observed during the observations. In the observatory in Melbourne during the time in question disturbances of considerable strength were not reported. After a last thorough examination of the observations, the magnetic elements for the time span 13th to 19th April 1864 for point A are as follows:

Magnetic declination	10°25.15' E
Horizontal intensity	(2.051 27 G E)
	4.448 83 British Units (E E)
Magnetic inclination	70°47.93' S.

It might be of general interest to add here something about the secular changes of the magnetic elements for the epoch 1846.3/64.3[10]. For May 1845 the value of the magnetic declination was 9°57.15' for Hobarton. This value, in combination with the values of the magnetic declination in single series determined by me, arrives at the following values for the secular change:

1. series 13 April	10°22.33' E	secular change	+1.33'
2. series 13 "	10°22.80' E	"	1.37
3. series 14 "	10°25.98' E	"	1.52
4. series 14 "	10°25.98' E	"	1.52
5. series 15 "	10°28.15' E	"	1.63
6. series 15 "	10°25.82' E	"	1.38
7. series 16 "	10°24.04' E	"	1.42
Average value	10°25.15' E	secular change	+1.453

Horizontal intensity. From the above observations of the value of horizontal intensity, combined with the value of the horizontal intensity for 1846.3, H = 4.4895 E E (Hobarton observations, Vol. I, p. 39) the secular change of 0.0023 E E (0.001 05 G E) decrease can be derived: furthermore it can be derived that the decrease per year is 0.00051 of the horizontal force.[11]

Magnetic inclination. The secular change of this element derives from the observations in Hobarton, according to which for March 1864 it is 70°34.03', combined with my observation at 70°47.93' for the epoch of 12th to 19th April 1864[12], to 0.70' increasing, a value, which almost completely converges with the value for Melbourne for the epoch 1858/64, that is 0.70' increasing.[13] In contrast, the observation in Hobarton has a different value, that is, a decrease in the inclination of 0.067'[14] during the epoch 1841/48.

One can deduce from this that the secular change of inclination is very small, the value it actually has could only be determined by a new examination.

It is now recommended, bearing in mind the details mentioned before, to add various things in translation from the report to Sir Edward Sabine mentioned before, keeping in mind that repetitions cannot be avoided:

"Soon after my arrival in Hobarton I examined, as thoroughly as possible, the geological formation of the surroundings of the former observatory for the purpose of finding possible influences of the magnetic observations exerted by the formations. It was quite impossible to arrive at an unquestionable result at the exact position of the former

observatory. Because changes due to erection of the new Government House would exert a disturbance, one could only observe at some distance of it. As the most suitable position a point, at a distance of 197 m S 4°25'E from the old observatory was chosen. This point lay on the same sandstone formation as the old observatory.

On R marked on the map there is a reservoir to which and from which different pipelines lead. These are marked on the map. Through the points M and N, which are situated on a road, is the approximate border between basalt and sandstone, which I determined approximately by trigonometry and marked by a dotted line on the map. This line, a continuation of the road, drawn through both points, is approximately perpendicular S 200 m from the old observatory. I mention the assumption that the basalt formation most probably extends around the beach[?] until again close to Government House. It was not possible for me to ascertain this as a fact, but I am inclined to presume so from the results of the magnetic observations. Should this be the case, then the sandstone formation (possibly Silurian) is very narrow, a presumption, that has considerable weight when the observation results are interpreted, because I found the basalt formation – as I could find out by experiment with a sample – had considerable influence on the magnetic needle, while the sandstone, as I found out through careful examination, was completely free of magnetic influence. Before I started a systematic observation series at point A I made these magnetic observations at a position which was close to the beach[?] and close to a battery. I marked this station with "Battery Point" and concluded that this lay at S 30°E at a distance of about 4260 English feet = 1296.8 m. The formation in the surrounding area of this position is basalt and forms the southernmost and lowest point of a basalt ridge, called Ross-Bank (Government Reserve). On the eastern slope of this ridge I made my observations at A. The described hill is approximately opposite the old observatory, at least 200 feet (60m) above the same and its eastern end is about four chains (80.4m) away.

As mentioned before, it would have been useful to make observations within the old observatory, but this was not possible.

Relatively free of influences was station A, at least to the same extent as the observatory of former times and I think that the observations conducted at this position give a good basis for a comparison with the observations which have been made in the observatory at the time of its operation. The bearings already reported elsewhere were:

Old Observatory	N 4°27.76' W
Tower of Government House	N 44°6.04' E
Trigonometric Station on Rumeney Hill	N 84°30.23' E

Following is an overview of the inclination observations conducted between 13 and 19 April 1864:

At point A	1. series	70°46.56' S
	2. "	70°49.30' S
Presumed inclination		70°47.93' S
At point C (see above)		71°18.12' S
At Battery Point (see above)		72°02.57' S

Point C lies, as indicated above, N 70°56.13' E at a distance of 235 m (11.7 chains) from A. Even though the geological formation at this position did not offer an unfavourable influence on the inclination, as far as could be observed from above (it was under agriculture), this magnetic element was however, as indicated above, not much greater in C than in A. This leads me to believe, that basalt formations were close by (perhaps not far below ground).

The considerable differences over such short distances as between A, C and Battery Point need to be noted carefully when considering the value of the points for absolute magnetic observations. We see from what was said before, that close to the beach[?] and particularly towards the south, the magnetic inclination increases quite considerably, which may be caused by the basalt. How far this influence stretches to the old magnetic observatory cannot be determined by the present observations. Because greatest care was taken that no other disturbances than those by geological formations occurred, the results stated can be seen as reliable.

As stated above, I observed in Launceston the inclination at 70°4.65' S, a value which, when compared with point A in Hobarton, is only about 40' smaller, while the difference in latitude of 83' lets one assume, that the inclination in Launceston would be considerably less, something that can be attributed to the considerable influence of the basalt …

If we summarize the result of this interesting observation we see that point A delivers good consistent results, which we can also conclude to have been true from the position of the former observatory. Station B, situated between the old observatory and A, also provides consistent values of the observed declination and can be said to be normal. Unfortunately no inclination observations could be executed at B. The horizontal intensity does not seem to have major differences at B when compared to A. All three points are situated on a small strip of Silurian, which was discussed above. Point C is different, in that there is no great deviation in horizontal component, but both magnetic declination and inclination elements seem greatly disturbed taking into account the short distance from the stations mentioned previously. The inclination is considerably different from what is considered normal, while the horizontal component cannot be viewed as undisturbed …

In the introductory remark I mentioned that I had conducted a thorough magnetic investigation of the area before the observatory in Melbourne was erected. I like to add, that there, on the sandstone formation of the left bank of the Yarra-Yarra River, similar contrasts were observed with results of observations taken on basalt (right river bank).

The values of the inclination, from the basalt stone were up to 67°19.47' S while on the Silurian area they were only 67°6.97' S.

The large masses of old and high volcanic rock in the vicinity of Melbourne and to the west of the meridian of the University exert strong influences on the magnetic elements, while to the east, on sandstone, the magnetic elements exhibit normal values.[15]

The observations conducted 41 years ago, close to a magnetic observatory which once was world famous, are the subject of this small publication and I will be completely rewarded for my work of checking and calculating, if because of it, others will take great care considering the geological formations, when erecting geomagnetic observatories.

After I concluded my observations in Hobarton and I collected several data to work with I farewelled the beautiful Hobarton to return to Melbourne. The return journey took place on a Tasmanian steamer in very favourable weather. I enjoyed the journey alongside the picturesque eastern coast of Tasmania with its basalt columns of colossal dimensions very much. After a 1½ day journey we reached the landing spot at Yarra-Yarra. My first task was to make the necessary observations and calibrations in the observatory in Melbourne. The next days and weeks before

my departure to Europe on 21st June 1864 were dedicated to this important work.

Footnotes

1 Observations made at the magnetical and meteorological observatory at Hobarton, in van Diemens-Island and by the Antarctic naval Expedition – Printed by order of Her Majestys Government under the Superintendence of Lieut.-Colonel Edward Sabine of the Royal Artillery. III Volumes, London 1850. Commencing 1841, ending 1848. (original)
2 First annual report of the board of visitors, Melbourne Victoria 1860/61. (original)
3 G. Neumayer, Discussion of the meteorological and magnetical observations, made at the Flagstaff Observatory, Melbourne, during the years 1858–1863, Mannheim 1867. (original)
4 G. Neumayer, Results of the Magnetic Survey of the Colony of Victoria, executed during the years 1858–1864. Mannheim 1868, S. 196. (original).
5 As given in the Hobarton-pamphlet the location of the observatory is: Latitude 42°52.5'S; longitude 147°27.5'E and 105 English feet above sea level. Vol. I of the Hobarton observations, p. X.
6 As can be seen from the various observations, this aim could not be quite achieved, because the position on the respective observation days proved to be slightly different.
7 Applying the mean of the torsion.
8 Average of two readings (10° 26.15', 10° 25.82')
9 The distance between A and B was measured to be 190 feet and 3.6 inch (58 m) (see above).
10 Neumayer, "Magnetic survey of Victoria" p. 199 and "Hobarton Observations", Vol. I p. 22, where for the epoch 1843/48 +1.46' (increasing) is given as the secular change for the magnetic declination, that means almost perfect agreement with the secular change deduced by myself (see further down).
11 Neumayer, "Magnetic Survey of Victoria", p. 196.
12 "Hobarton Observations", vol. I, p. 83.
13 Neumayer, "Discussions", Vol. II, p. 157.
14 "Hobarton Observations", Vol. I, p. 84, after which the magnetic inclination decreases by 0.067' per year. Whether the inclination at Station A could have been greater because of the proximity of the nearby basalt, cannot be evaluated anymore.
15 "Magnetic survey", p. 198 and in the associated report.

PRESENTATION TO THE MELBOURNE CHAMBER OF COMMERCE

Neumayer was a tireless chronicler of phenomena, be they meteorology, magnetic parameters, or even ship arrivals and departures. He produced a register summarising the arrival and departure of 300 voyages from Europe to Australia including references to latitude and longitude on a daily basis and other data. The object of this research was to establish the optimum sailing route between Europe and Australia, following the principles developed by the oceanographer M.F. Maury (Home 1991). On departing Australia, he presented a copy to the Melbourne Chamber of Commerce and this is recorded in the *Cornwall Chronicle* (Launceston) of Wednesday, 1 June 1864 under the heading "Professor Neumayer's gift to the Chamber". It is a re-published version of an article that appeared in the *Argus* (Melbourne) on 19 May 1864:

> The following communication was read from Professor Neumayer:–
> Montpelier-terrace, South Yarra. May 16.
> Sir,– As my stay in the colony is drawing to a close, and I am about to return to Europe, with the special object of publishing the result of my labours in connexion with the Magnetic and Nautical Observatory and the magnetic survey of the colony. I feel it incumbent upon me to address you as representant of a body who, ever since my first arrival in the colony, gave me a most cordial support in carrying out the objects of my visit to this part of the globe.
>
> I respectfully request you to express to the Chamber of Commerce my sense of appreciation of the kindness extended to me, and anxious still further to substantiate my feelings by a small token of gratitude, I have prepared the accompanying register of voyages from Europe to Australia, which I beg you to accept on behalf of the Chamber of Commerce. In years to come such a well-authenticated record of the voyages named will prove highly valuable, by aiding in still further developing and perfecting the means of communication with the mother country.
>
> Based upon this document is my discussion of 300 voyages, which resulted in the construction of my average route and trade chart, hereby also presented to the Chamber of Commerce. It remains only for me to mention that my work on meteorology and navigation, of which the above-named chart forms a part, will be duly forwarded to you when printed and ready for distribution, which will be in less than a fortnight.
>
> Requesting you again to express to the Chamber of Commerce my most cordial thanks,
> I remain Sir, your most obedient servant,
> NEUMAYER.

To the President of the Chamber of Commerce, Melbourne.

A description of the valuable gift of Professor Neumayer will not be out of place here. The register contains 300 named voyages from Europe to Australia. The longitudes and latitudes for each day are given; and the crossing of the line and the passing of the meridians of Greenwich and the Cape are indicated by red lines, thereby facilitating the comparison of the voyages. Below the names of the ships are inserted the exact dates of departure and arrival; and the seasons in which the voyages were made are shown by the colour of the fields bearing the geographical position. The seasons are those of the northern hemisphere, green representing spring; red, summer; blue, autumn; and white, winter. This is explained on the border surrounding the whole, which is a fixture. The charts are mounted on canvas, and move round two rollers, so that sixty voyages are at once exhibited, and may be compared. The whole is tastefully ornamented with a border emblematic of ocean navigation, and is in a large cedar case covered with glass. The heading bears the following inscription.–"Three hundred voyages from Europe to Australia, 1858–1862." and beneath,

the words--:Presented to the Chamber of Commerce of Melbourne, by George Neumayer, director of the Flagstaff Observatory." The writing is from the pen of Mr. C. Willberg, and the construction of the case and mounting of the charts were entrusted to Mr. Grimaldi of Queen-street, and the workmanship reflects great credit on both these gentlemen.

On the motion of Mr. Bligh, seconded by Mr. De Little, the secretary was instructed to convey to Professor Neumayer the high appreciation entertained of his very valuable gift, and their reciprocation of the feeling manifested by him towards the Chamber.

CONCLUSIONS

There are two facets to Neumayer's association with Tasmania. He visited Tasmania, both Launceston and Hobart, between 8 and 19 April 1864 and made a significant contribution to knowledge of the magnetic parameters as close as practicable to the site of the earlier Rossbank Observatory, some 10 years after the observatory had ceased operation. His studies not only provided a younger set of readings but also a means of integrating the Tasmanian data with a potentially longer dataset developed in Melbourne, and thus to the global network.

This paper gives a translation of his 1905 German paper describing both the acquisition of the results but also comments on a few aspects of Tasmanian conditions at the time. He was given very able, willing assistance from those living here at the time.

Knowledge of the geological conditions relevant to the operation of a magnetic observatory at the site of the Rossbank Observatory were not well known either at the time of the original establishment or later during Neumayer's sojourn.

His presentation to the Melbourne Chamber of Commerce was recorded in the Launceston newspaper *The Cornwall Chronicle* of 1 June 1864, immediately before his return to Europe at the end of his five years in Australia.

His contributions to the knowledge of Tasmanian magnetic characteristics deserve to be better known.

ACKNOWLEDGEMENTS

This project has benefited greatly from the assistance of many people. Its genesis lay in discussions with Professor R. Home of the University of Melbourne, an authority on Neumayer's work in Australia. Dr Eva Meidl of the School of Modern Languages, University of Tasmania, provided the initial translation of the text which was identified by Dr Reinhard Krause, Alfred-Wegener Institute, Bremerhaven, Germany, and found for me by Stephen Pendlebury, Bureau of Meteorology, Hobart. Dr Charles Barton, Canberra, then gave advice on who to contact regarding the translation of nineteenth-century magnetic technical terms and identified Professor Joachim Linthe, GeoForschung-Zentrum, Potsdam, who provided the information requested in a very short time. Dr Jan Lieser, Institute for Antarctic and Southern Ocean Studies at the University of Tasmania, helped with some of the translation. Jeff Powell of the Powerhouse Museum, Sydney, kindly searched out issues relating to Cobbs Coach and the Imperial. Henk Brolsma of the Australian Antarctic Division helped identify the chimney referred to in the original paper. Without every member of this team, the project would never have come to fruition. The paper has benefited by reviews by Professor M. Roe and Professor R. Home.

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